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A mathematical hydrological model for the ungauged catchment

A mathematical hydrological model for the ungauged catchment

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Memorandum

This thesis is the original work of the candidate except where acknowledgement is given, and has not been submitted for a higher degree in this or in any other University.

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July 1985

Synopsis

In geographical hydrology there has been more interest in scientific rather than in practical application of mathematical models of catchment hydrology. This thesis emphasizes the importance of examining the potential of developments in scientific research programmes for practical hydrological applications, and in particular provides discussion upon the following five issues:

1. The application of hydrological models to ungauged catchments where no historical streamflow record is available for calibration.
2. The potential of hydrological models for routine and operational application. This application limits the data and computer resources which are available for use.
3. The development and application of a thorough model evaluation strategy which examines the suitability of a model in the context of a specific application requirement.
4. The selection of a conceptually sound model structure.
5. The development and evaluation of a suitable methodology for the incorporation of the spatial variability of catchments into hydrological models.

To provide a basis for the discussion of these five issues, this thesis provides the details of the modification of a currently used hydrological model, HYMO. The modification of this model involves the replacement of the empirical curve number model for runoff derivation with a physically based parameter infiltration model. A number of comparisons of HYMO and the modified version, HYMO2, indicates that conceptual, parameter estimation, prediction, and sensitivity improvements have indeed been secured by the development of the modified model.

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Introduction:
Requirements of a mathematical model of catchment hydrology

The development of mathematical hydrology models is one specific area of interest in geographical hydrology which has experienced an increase in research activity since the early 1970's (Ward, 1979, 1980). The major thrust of this activity has been directed towards the development of mathematical models which realize scientific and research objectives. These models are therefore designed to improve our theoretical understanding and explanation of the detailed causal mechanisms of hydrological processes. Consequently, highly complex mathematical models have emerged which describe the flow of water over and within the soil, through channel reaches, and through reservoirs in terms of the principles of continuum mechanics: the conservation of mass, energy, and momentum. These models typically demand copious and reliable catchment, meteorological, and historical streamflow data for the assignment of parameter values, extensive computer resources to run the simulations, and it is common that parameter estimation and application procedures require detailed and extensive experience of the model and its application. Thus many of these models are restricted in their application to heavily instrumented environments, to limited spatial scales, and commonly to the individual or organization involved directly in the design and development of the model and who is therefore most familiar with its capabilities and limitatations.

These models do fulfil an essential research role in geographical hydrology, but there is also a need to develop models which directly fulfil more practical goals. This thesis proposes that geographical hydrology can provide the basis for significant improvements in the application and implementation of mathematical hydrological models for the solution of operational forecasting problems at a catchment scale.

This thesis argues that it is vital that practical issues be adequately identified and associated with research developments.

In particular, five fundamental issues can be identified in geographical hydrological modelling which have to date received neither extensive comment, nor direct attention. These are:

1 The definition and development of mathematical hydrological models which are suitable for application to the ungauged catchment. In this application, catchment and meterological data are typically of limited quantity and quality, and more specifically, no historical streamflow data are available for the calibration of model parameters.

2 The detailed consideration of operational requirements. This requires the development of mathematical hydrological models which fulfil the constraints that such an application imposes upon data, computer resources, and the technical competence of the eventual user of the model.

3 The definition and application of a thorough model evaluation strategy which assesses if the mathematical model is logically sound in the context of the intended application, if the computer implementation has been correctly effected and operates as the mathematical model has defined, and finally, if the mathematical model and its computer implementation provide reliable results.

4 The mathematical hydrological model selected for the ungauged and operational application must have a structure which is conceptually and philosophically sound.

5 Within the context of any proposed application, consideration must be given to the effects of spatial variability of catchment and

meterological characteristics. A methodology which incorporates the effects of these into the model structure must be designed and evaluated.

Discussion and comment upon these five issues will be provided in this thesis. In order to explore these five issues in more detail, certain developments to a currently utilized mathematical hydrological model, HYMO, have been undertaken. HYMO (HYdrograph MOdel) has been developed by Williams and Hann (1972, 1973) to provide flood forecasts for agricultural watersheds. HYMO is suitable for application to the ungauged catchment, it is presented as a computer package in which attention has been paid to ease of use, and a degree of model evaluation has been undertaken. However, the model has not been noted for the accuracy of predictions, and it is proposed that certain improvements can be achieved.

The aim of the model development programme which will be used to illustrate these five issues may therefore be more clearly defined as the development of a mathematical hydrological model which can provide a flood forecast, i.e. an estimate of the magnitude and timing of the response of river discharge to a storm event (Nash and Sutcliffe, 1969), at selected points along the channel, which can be considered to be accurate, and which fulfils the following criteria:

1 The model is applicable to the ungauged catchment.

2 The model meets operational requirements.

3 The model design and implementation facilitates a thorough model evaluation.

4 The most appropriate model structure is selected.

5 The model takes spatial variability into account.

This introductory chapter is divided into six sections. The first five provide comment and discussion on each of the five issues which have been introduced above: application to the ungauged catchment, operational requirements, model evaluation, model structure, and spatial variability. The sixth section summarizes the recommendations which are to be considered in the development of the modified version of HYMO.

1.1 Application to the ungauged catchment

The first criteria which the proposed modified version of HYMO should fulfil is that it should be suitable for application to the ungauged catchment. The application of mathematical hydrological models for streamflow forecasting in ungauged catchments is considered to be one of the most difficult, and consequently one of the most challenging, problems in hydrology. However this problem remains largely unsolved (Verma and Advani, 1973) and as Beven (1983) remarked, there has been very little activity aimed specifically at meeting this challenge. For these reasons, it is seen to be necessary to develop such a model.

For the purposes of this research programme, an ungauged catchment is considered to be one in which:

1 There is no streamflow gauging structure. No historical or current discharge information is available.

2 The only catchment information available is that which can be determined from a topography and soils map. A field measurement programme cannot be implemented.

3 Precipitation data are available, although the rain gauge or raingauges may not necessarily be located within the catchment.

This section reviews a number of ungauged catchment models which have been reported in the literature. A selection of these is provided in tables 1 to 3. These examples will be used to illustrate that for two major reasons, none of these models can be considered to be appropriate for flood forecasting in the ungauged catchment, as defined above. They either require streamflow discharge data for calibration, or they require more detailed catchment information than would normally be available.

Figure 1 serves to summarize and clarify the framework within which the models in tables 1 to 3 are considered. Three possible application requirements in the ungauged catchment will be examined here: the prediction of various flood statistics (table 1), forecasting single event responses (table 2), and forecasting a continuous discharge record (table 3). For the first application, only calibrated parameter models are available, but for the second and third, there is a choice of either calibrated or physically based parameter models.

Prior to a detailed discussion of the information provided in tables 1 to 3, it is necessary to consider the differences between the two types of model, calibrated and physically based parameter, which, as indicated in figure 1, can be applied to the ungauged catchment. Hydrology models have been classified in the literature according to a large number of criteria, but for the purposes of this discussion for ungauged catchment application, they are classified according to the method by which the model parameters are estimated.

In the derivation of any catchment mathematical hydrological model, the catchment is considered as a system in which hydrological inputs (rainfall for example) are related to outputs (stream discharge). The nature of this relationship is described by a series of mathematical statements and a model may be considered to lie anywhere along a spectrum of complexity. At the very basic level, many simplifying assumptions can be made about the operation of the system, and a simple equation which involves a single parameter may only be required. Alternatively, an attempt may be made to model the complexity of the processes which are operating within the system. This would produce a complex series of equations involving a very large number of parameters.

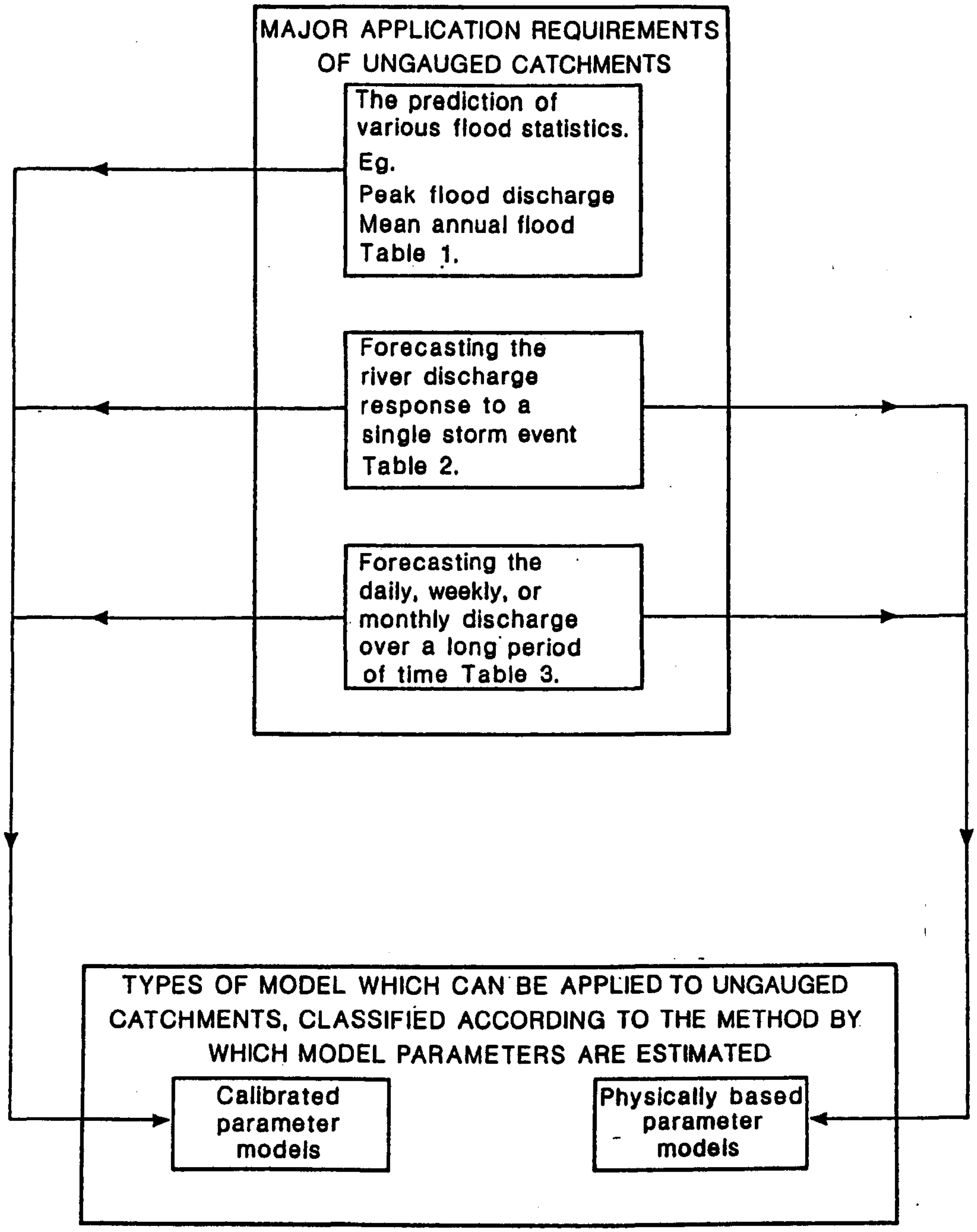

Figure 1: A framework within which ungauged catchment models may be considered

In order to apply any model to a catchment, values for the model parameters must be defined. Some model parameters are physically based and represent catchment characteristics which can be measured, catchment area for example. Some model parameters however are not so easily estimated. All models simplify reality and consequently parameters do not always have physical interpretation, but may be an index which represents the net effect of a number of catchment characteristics, or a property which is not measurable at the scale for which it is required. In this case, the parameter value is derived by calibration. The parameters are estimated by comparing a series of measured and predicted hydrological outputs (stream discharge) which correspond to a given series of inputs (precipitation), and the parameter values are adjusted until the predicted output fits the observed. Calibrated parameter models are therefore inappropriate for the ungauged catchment application where, as has been stressed, no measured stream discharge data are available. However, in addition, the procedure of calibration suffers a number of problems which will now be discussed.

The major aim in calibrating a model to a particular catchment is to obtain a unique parameter set which is physically realistic. The main problem in calibration is that of an inability to obtain such a solution. In practice, a unique solution is not attainable; several combinations of parameter values can produce the same result. Calibrated parameter values are not always physically realistic, but may operate to balance out errors which occur in the data or in the model structure. Three reasons can be proposed to account for this problem:

1 The quantity and quality of the data used for calibration can inhibit the realization of a unique and conceptually realistic parameter set. These data will contain measurement error and Ibbitt (1972) demonstrated that errors in the streamflow record significantly influence the accuracy of parameter estimates. Additionally, the data may be poor 'activating' data in that if the data do not adequately represent all conditions for which the model is designed, certain processes may not be activated when the model is run. The

parameters which describe this nonactivated process cannot therefore be calibrated.

2 Error in the model structure inhibits the attainment of the unique solution (Sorooshian and Gupta, 1983). Imperfect representation of the physical processes, and a large number of interacting parameters will adversly affect the success of the calibration procedure. Sorooshian and Gupta (1983) stressed that the design and development of hydrological models do not always reflect the current capabilities and limitations of calibration techniques.

3 The hydrological system is almost always indeterminate; the number of model parameters is greater than the number of equations or sources of information about the system (Kisiel, 1971). There are a large number of degrees of freedom and consequently an infinite number of solutions is possible. Choice of the optimum parameter set relies heavily upon the calibration procedure utilized. The calibration procedure involves two stages; firstly, the selection of an objective function, usually a certain combination of errors (deviations of the predicted from the measured values), and secondly, a procedure which searches for that combination of parameter values which minimizes this objective function. This search procedure may also include the setting of constraints on parameter values to ensure that physically realistic values are maintained.

There are very few recommendations which suggest the most suitable objective function for hydrological modelling (Flemming, 1975; Morel-Seytoux, 1982). The choice of objective function does influence the optimum parameter values (Dawdy and Thompson, 1967; Sorooshian et al, 1983), however, there have been very few studies which have explored the relative merits of the various objective functions.

There are three possible procedures for searching for the optimum parameter set. Where the model is simple and linear, analytical techniques such as linear programming or calculus may be used. For more complex models, automatic techniques are available. A computer program is used to adjust parameter values systematically to search for the optimum and to test against the objective function. The major problem with this technique is that there are several features of the response surface, formed when the objective function is plotted against the parameter values, which confound the search technique, and which prevent the location of the true optimum. In this context, Ibbitt and O'Donnell (1971) drew attention to the influence of local optima, saddle points, extended valleys, plateaus, and pot holes. These features are related to errors in data and in model specification. Very complex models which contain many unknown parameters, which may not necessarily be independent, cannot be automatically optimized. In this case, manual calibration has to be used. This is not always a systematic procedure and the ability of the operator to adjust the parameter values to derive that combination which provides the best estimates is largely a function of the skill and experience of the operator. It requires a familiarity with the manner in which the catchment and the model operate and interact for the particular application. Indeed, it does not always involve an objective evaluation of an objective function. A subjective assessment, implicit in the operator's knowledge of the system, is also involved.

Three examples from the literature will serve to illustrate these problems in model calibration. Firstly, although Johnston and Pilgrim (1976) are experienced hydrologists, they failed to find the true optimum parameter set for a nine parameter version of the Boughton Hydrology model in over two years of full time effort. Secondly, Pickup (1977) has demonstrated the variety of optimum parameter sets which can be derived for the twelve parameter Boughton model, depending on the calibration procedure which is used. Thirdly, Beven (1985) discusses the hypothetical situation where a model which is only applicable for catchments dominated by surface flow is calibrated with data from a catchment experiencing subsurface flow. The model may predict the catchment response with some success, but this has been achieved by just fitting the storage and time delay characteristics of the observed response. The fitted model and the calibrated parameter values are not physically realistic.

It is generally considered that most calibration efforts do not emphasize sufficiently the search for a unique and conceptually realistic parameter set, but settle on that parameter set which provides the best fit. This has the result that the model has a very poor forecasting ability.

Support for the development of models which are designed specifically to incorporate physically based parameters can be found in a number of locations in the literature (Beven, 1975; Chapman, 1975; Jones, 1976; Manley, 1978; Beven and Kirkby, 1979; Beven and O'Connell, 1982; Anderson and Howes, in press). Klemeš (1982) has emphasized that advancement will not be achieved merely by refinement or elaboration of empirical hydrological models, accompanied by a progression further up the "...dead-end street of parameter optimization..." (Klemeš, 1982a, p102).

This discussion has illustrated the differences between physically based parameter models and calibrated parameter models. The unsuitability of calibrated parameter models for the ungauged catchment application must be stressed. Attention will now be focused upon an examination of the selection of ungauged catchment models which are currently available, and which are illustrated in tables 1 to 3.

(The symbols which are used and defined in each table in this thesis do not apply to any other table or equation which may appear in the text. In order that the original form of the equations be maintained, both imperial and metric units are used.)

Table 1 provides a number of examples of models which have been used to estimate flood statistics such as mean annual flood and peak flood discharge for ungauged catchments. Associated with the estimate of each statistic, two types of formula exist: runoff formula, where discharge is only related to catchment characteristics, and precipitation formula,

Table 1: Hydological models for the prediction of various flood statistics in the ungauged catchment

	Calibration details	Formula
Determination of mean annual flood ($\bar{Q}$)		
Runoff formulae		
Nash and Shaw (1965)	57 gauged catchments in Great Britain 7.8-9900 km^2	$\bar{Q}=0.76(AREA)^{0.74}$
Cole (1965)	56 gauged catchments in Great Britain	$\bar{Q}=c(AREA)$ 'c' is a regional coefficient
Precipitation formulae		
Benson (1962)	164 gauged catchments in humid area of New England 4.28-25022.0 km^2	$\bar{Q}_T=aA^bS^cSt^dI^et^fO^g$ Lower case letters, empirical coefficients
Benson (1964)	219 gauged catchments in semi-arid areas of Texas and New Mexico 2.59-90650.0 km^2	Rainflood area: $\bar{Q}_T=aA^bS^cSt^dI^eL^fR^gN^h$ Snowmelt area: $\bar{Q}_T=aA^bS^cSt^dP^eE^fN^g$
NERC (1975)	500 gauged catchments in Great Britain and Ireland	

$$\bar{Q}= RM(AREA)^{.94}(STMFRQ)^{.27}(S1085)^{.16}(SOIL)^{1.23}(RSMD)^{1.03}(1+LAKE)^{-.85}$$

RM is a regional coefficient derived from the following table:

Region	RM
N Scotland	.0186
E Anglia	.0153
S Coast	.0234
S W England	.0315
Central Region	.0213
Ireland	.0172
Average countrywide	.0201

For Thames, Lee and Essex area:

$$\bar{Q}=.302(AREA)^{.7}(STMFRQ)^{.52}(1+URBAN)^{2.5}$$

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	Calibration details	Formula
Determination of peak flood discharge (Q) and flood frequencies		
Runoff formulae		
Inglis Formula Verma and Advani (1973)	Bombay area, India Fan shaped catchments	$Qmet=125(AREA)/(AREA+4)^{0.5}$
Dickens Formula Verma and Advani (1973)	Northern and central India	$Qmet=c(AREA)^{0.75}$ The coefficient 'c' varies from 1.66 to 10.5
Jarvis Formula Verma and Advani (1973)	American catchments	Qmet=1.77b(AREA) b is a coefficient
Armentrout and Bissell (1970)	32 gauged catchments in Maryland and Virginia All natural streams 2.59-25.9 km^2	$q_{(10)}=0.035(S)^{0.75}$ $q_{(25)}=0.046(S)^{0.77}$ $q_{(50)}=0.054(S)^{0.8}$
Precipitation formulae		
Rational Formula		Qimp = c.Is.Aa 'c' represents the % of rainfall which becomes runoff and varies from .05 for flat sandy areas, to .95 for urban areas
	20 gauged urban areas in and around Baltimore .87-620.8 km^2	Formula for 'c': Schaake et al (1967) c=0.14+0.65(IMP)+0.05(S)
Interpolation procedures		
Crippen and Conrad (1977)	883 gauged catchments in the States Maximum 25,900 km^2	Flood frequency curves are provided for each physiographic region
NERC (1975)	500 gauged catchments in Great Britain and Ireland	Flood frequency curves for all 10 regions

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Key for table 1 ... continued from previous page

$\bar{Q}$	mean annual flood
$\bar{Q}_{(T)}$	T year mean annual flood
Qmet	peak flood discharge ($m^3 sec^{-1}$)
Qimp	peak flood discharge ($ft^3 sec^{-1}$)
$q_{(n)}$	unit runoff ($ft^3 sec^{-1} acre^{-1}$) corresponding to n recurrence interval
S	main channel slope ($ft\ mile^{-1}$)
S1085	mainstream slope between 10 and 85 percentiles of main stream length from gauge
AREA	catchment area (km^2)
Aa	catchment area (acres)
A	catchment area ($miles^2$)
IMP	% impervious areas
URBAN	% urban areas
St	% lakes and ponds plus 0.5%
LAKE	% catchment draining through lake or reservoir
Is	rainfall intensity ($ins\ hr^{-1}$) during time to concentration
I	T year 24 hour rainfall intensity
RSMD	Net 1 day rainfall of 5 year return period
P	mean annual precipitation inches
R	ratio runoff to precipitation during most annual mean runoff
N	mean annual number of thunderstorm days
t	average January degrees below freezing (^oF)
O	orographic factor
L	main channel length (miles)
E	altitude (ft above mean sea level)
H	basin rise (ft)
STMFRQ	number of stream junctions as shown on 1:25,000 divided by catchment area
SOIL	soil index

where some measure of rainfall is included in the independent variables. Interpolation procedures are used to derive flood frequency curves for regions. These tables do not document all flood statistics models which have been applied to the ungauged catchment; Gray and Wigham (1970), and McCuen et al (1977) provide more examples.

All of the parameters in these models in table 1 have been calibrated. They are optimized by analytical techniques using least squares objective functions. For the ungauged catchment, there are consequently a number of problems with their application.

They are calibrated models which strictly speaking are applicable only for those catchments and conditions for which they were derived. Relationships cannot simply be extrapolated to other catchments based on the assumption that behaviour will be similar. This is not the case, most hydrological systems are inherently nonlinear and time variant. It cannot be over emphasized that these are regression rather than functional relationships, and beyond the range of their empirical basis, prediction relies solely on the mathematical technique. Due to the simplicity of the models and the assumptions which are made, these formulae can result in very large prediction errors. The Natural Environment Research Council (NERC, 1975) stressed this unreliability and recommended that where a flood estimate is required at a site for engineering design purposes, that a gauging structure should be constructed to provide a discharge record. Direct analysis of this will be more reliable. However, in contrast to this, Heiler (1975) considered that empirical relationships between mean annual flood and catchment area are satisfactory for the design of water control structures in ungauged catchments in Malaysia.

Considerable knowledge is necessary to estimate the coefficients for application to a particular catchment. For example, 'c' in the Rational Formula can be derived from tables (Chow, 1964) or from formula such as that provided by Schaake et al (1967), but for any one catchment, the value varies with storm frequency and characteristics. Schaake et al (1967) warned that their relationship for 'c' is valid only for urban catchments (0.87 to 620.8 square km) which experience storm patterns characteristic of the Baltimore region in the United States of America, and should be used with extreme caution elsewhere. Many authors have attempted to regionalize the coefficients (Cole, 1965; NERC, 1975) by calibrating their model to a number of gauged catchments in a region which is assumed to exhibit similar hydrological and meteorological conditions. In this context, Allison (1967) stressed that the reliability of the regional coefficients can be considered to be inversely proportional to the size of region for which they are derived.

Table 2 provides some examples of models which have been used to estimate the discharge response of an ungauged catchment, at its outlet, to a single storm event. This particular application is of interest in this thesis. In order to achieve this estimate, it is necessary to determine the runoff for the catchment area and to transform this into the streamflow at the outlet. Both calibrated and physically based parameter models are available.

The calibrated parameter models such as HYMO and NERC (1975) derive runoff from an empirical formula which has been calibrated for a number of gauged catchments, and is then extrapolated to the ungauged catchment. The routing and distribution of this runoff at the outlet are achieved by convolving this runoff with the catchment unit hydrograph. Again, the unit hydrograph procedure was not designed specifically for ungauged catchments, but for those where a rainfall and runoff record is available. Its application to the ungauged catchment has been achieved by correlating the unit hydrograph parameters, peak discharge and time to peak, to measurable catchment characteristics (Snyder, 1938; Clarke, 1945; Nash, 1960) or by the synthesis of unit hydrographs for a region to a dimensionless hydrograph (Gray, 1961). When peak discharge and time to peak have been measured or estimated, the unit hydrograph can be derived from the dimensionless unit hydrograph, for any given catchment. HYMO uses a dimensionless unit hydrograph and the NERC model uses the Clarke model. DeVries (1982) also discussed in general terms an ungauged application of HEC-1

Table 2: Hydrological models for forecasting the river discharge response to a single storm event in the ungauged catchment

Models containing calibrated parameters		
	Synthetic unit hydrograph	Runoff generation
HYMO Williams and Hann (1973)	Dimensionless unit hydrograph described by 2-parameter gamma curve calibrated for 34 catchments in Texas, Oklahoma, Arkansas, Louisiana, Mississippi and Tennesse $1.3\text{–}64.8\ km^2$	Soil Conservation Service Curve Number Method
NERC (1975)	Clarkes unit hydrograph parameters calibrated to 500 catchments in Great Britain and Ireland Maximum $500\ km^2$	Empirical runoff formula also calibrated to the 500 catchments

Models containing physically based parameters		
	Applications	Parameter estimation
Engman and Rogowski (1974)	Applied to 1 watershed 58.3 ha	Require field measurements of initial moisture content. There are also problem with ungauged estimates of Mannings ´n´ for overland flow and channel
Beven (1975)	Applied to 1 watershed	Unless very detailed measurements are available, it is necessary to calibrate this model

(Hydrologic Engineering Center, 1981). This model is similar in structure to HYMO. The regional parameters are derived for the unit hydrograph and the loss function by calibration of the model to gauged catchments. DeVries (1982) stressed however, that predictions will be improved if all the available data are used in the calibration, thus implying that significant error is associated with an ungauged application of HEC-1.

The major problem with models such as HYMO and NERC (1975) is that because they are calibrated, there is no physical justification for the extrapolation of the empirical relationships derived for gauged catchments to the ungauged catchment. Where this is attempted, error is introduced and questions concerning reliability are raised.

Two physically based parameter models are also indicated in table 2. Rainfall excess is predicted from equations which describe the physical behaviour of infiltration in the soils, and this is routed over the soil surface and through the stream channels using kinematic routing techniques. The parameters in these models can be measured in the field and therefore the model could be considered to be appropriate for application to the ungauged catchment. The major problem however is one of estimating parameter values which are accurate enough for the model to be of value. Engman and Rogowski (1974) stressed that detailed field measurement of initial soil moisture conditions is essential for accurate predictions by their model. Beven (1975) has also suggested that unless very detailed and accurate measurements are available from a field measurement programme, that calibration is necessary to apply his particular model. Although these models are physically based, they are clearly not suitable for the ungauged catchment application considered here, as a detailed field measurement programme is necessary.

Table 3 provides some examples of models which have been used for continuous simulation of stream discharge in the ungauged catchment and again, both calibrated and physically based parameter models are available. The physically based parameter models include those designed purely for hydrological modelling and those designed to supply a

Table 3: Hydrological models for forecasting daily, weekly, or monthly discharge, for a period of time, in the ungauged catchment

	Application details	Parameter estimation
Models containing calibrated parameters		
USDAHL-74 Nicks et al (1977)	Parameters calibrated on 12 catchments in the great plains 5.1-47,140 ha	From maps and USDA tables Flow recession and ground water estimated from nearby gauged basin or from regional characteristics
USDAHL-74 Crow et al (1978)	Parameters calibrated for 1 catchment	Details used to simulate runoff for 2 others, 2 and 24 km away
Stanford Watershed Model Ross (1970)	17 watersheds in Kentucky Maximum 64.8 km^2	Correlated optimum parameters with basin properties for use in ungauged basins
4-parameter water yeild model Jarboe and Haan (1974)	Parameters calibrated for 17 watersheds	Regression formula developed for all 4 parameters, used for ungauged application
Models with physically based parameters		
(a) For discharge estimates		
HYSIM Manley (1978)		All parameters measurable in field, 3 groundwater parameters estimated from nearby gauged catchment
WATSIM Aston and Dunin (1979, 1980) Dunin and Aston (1981) Aston et al (1980)		Parameter estimation requires some direct field measurement. Storage coefficient for overland flow requires calibration
TOPMODEL Beven and Kirkby (1976, 1979a, 1979b) Beven (1977a) Beven et al (1984)	For small to medium catchments in humid temperate areas	Parameters can be derived from field measurements but optimized parameters were found to provide better results

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	Application details	Parameter estimation
(b) Models which provide hydrological inputs for agricultural management systems and environmental impact assessment		
SPUR Hydrology Component Renard et al (1984)	Developed for rangeland management in south west United States	All parameters are derived from maps Problems with parameters such as degree of cracking and return flow travel time
CREAMS-1 CDRHM	Developed to evaluate agricultural management systems for small catchments	All estimated from maps
CREAMS-2 Smith (1983)	New capabilities including more physically based routines	For parameters not locally measurable a series of tables to be provided in the full documentation
SWAM DeCoursey (1982)	Based on CREAMS-2 for small watersheds	Designed for use without calibration. Tables supplied for parameter estimation

hydrological component for a larger agricultural or environmental management model.

In the case where a model has not been designed specifically for the ungauged catchment, but where calibration is necessary to provide parameter values, three solutions have been proposed.

1 The model is calibrated on a nearby, gauged catchment. The parameter values thus derived are used to derive the parameters for the ungauged catchment. It is necessary that the gauged catchment be both hydrologically and meteorologically similar to the ungauged, and that they are of the same general size. This strategy was adopted by Nicks et al (1977) and Crow et al (1978) in ungauged applications of USDAHL-74 (United States Department of Agriculture Hydrology Laboratory model - 1974). The estimation may take the form of a straight translation of values, or parameters may be subject to minor adjustments based on known hydrological differences.

2 For a given ´region´, a model may be calibrated with data from a number of different catchments and the so derived parameters are then correlated against measurable basin characteristics. These generalized relationships which are assumed to hold for regions exhibiting similar hydrological characteristics, are then used to provide parameters for the ungauged catchment. Examples of this procedure are provided by Ross (1970) for the Stanford Watershed Model and by Jarboe and Haan (1974) for a four parameter water yield model.

3 At a very generalized level, calibrated parameters can be estimated from tables. Certain parameters of the Stanford Watershed Model for example can be provided in this way (Ross, 1970).

Table 4 provides, in more detail, an example of the guidelines which might be provided to a user when applying a calibrated model to an ungauged application. The example is that provided by Ross (1970) for the Stanford Watershed Model. The parameters required by the model can

Table 4: Guidelines for parameter estimation for the Stanford Watershed Model (summarized from Ross, 1970)

Parameter		Method of estimation
A Parameters to be estimated directly from catchment		
AREA	Catchment area	Topography maps
FIMP	Impervious fraction of catchment	Aerial photography
FWTR	Water covered fraction of catchment	Topography maps and aerial photography
OFSS	Average slope of overland flow surfaces	Average a series of measurements made for a random set of points on topography map
OFSL	Average length of overland flow surfaces	Using technique descibed above for OFSS
CHCAP	Index of channel capacity - an estimate of flow at mouth of watershed	Hydraulic analysis of profile and cross section or estimate gauge height of bankfull flow from topography map
DIV	Daily flow diversion by water users. Diversion into stream considered positive	
B Parameters that have been calibrated and correlated to basin characteristics		
LZC	Lower zone soil moisture capacity	Related to available water capacity (AWC) LZC=-.7016+1.2404(AWC)
ETLF	Maximum evapotranspiration	Related to OFSS and forest cover. Forested bottomlands: ETLF=.3606-.5497(OFSS) Unforested bottomlands: ETLF=.2709-1.0192(OFSS)
BMIR	An infiltration index	Related to A horizon permeability (Pa) BMIR=2.3593(Pa)

Continued on following page ...

Table 4 ... continued from previous page

Parameter		Method of estimation
C Parameters to be estimated from tables		
VINTMR	Watershed interception volume storage capacity	Estimated from vegetation cover
OFMN	Mannings 'n' for overland flow on soil surfaces	Estimated from watershed surface
OFMNIS	Mannings 'n' for overland flow on impervious surfaces	Estimated from watershed surface
BFNLR BFRC	Baseflow recession parameters	Estimated from subsurface geology
BUZC	Basic capacity of upper zone soil surface to store water as interception and depression storage	Estimated from slope, forest cover and permeability
SUZC	Seasonal variation of soil surface moisture storage capacity	Estimated from slope, forest cover, and permeability
SIAC	Evapotranspiration - infiltration factor which takes seasonal variation into account	Estimated from percentage of forested area
D Parameters for which few operation guidelines provided		
GWETF	Estimation of current rate at which swamp vegetation is draining water from below water table	Trial and error estimation For most basins, best value is zero
SUBWF	Fraction of moisture entering groundwater which leaves basin as subsurface flow	Trial and error estimation For most basins, best value is zero
IFRC	Interflow recession	None
BIVF	Index controlling the time distribution and quantities of water entering interflow	None

Continued on following page ...

Table 4 ... continued from previous page

Parameter		Method of estimation
CSRX	Streamflow routing parameter, channel storage when flows are less than half capacity	None
FSRX	Streamflow routing parameter, channel and flood plain storage when flows are twice channel capacity	None

be divided into four groups. Group A are physically based and can be estimated directly from catchment maps or aerial photographs. Group B require calibration and a series of regression equations are provided for parameter estimation. Ross (1970) has calibrated the model to 17 rural watersheds in Kentucky in order to derive optimized values for these parameters. These were then regressed against basin characteristics. Parameters in group C can be estimated from tables. There remains however, group D, parameters for which no operational procedure for parameter estimation is provided.

The application to the ungauged catchment of such models whose parameters require calibration is clearly unsatisfactory. Pattison (1975) warned that the complexity of hydrological processes makes a straight transposition between gauged and ungauged catchments very dangerous and claims that there have been very few successful results in such extrapolations. Indeed, Jarboe and Haan (1974) found that using regression prediction equations for model parameters did not work successfully when the ungauged catchment differed in any way in terms of size, land use, or average depth of soil from the gauged catchments which were used in calibration.

There are a number of models in table 3 which have been designed specifically for applications where streamflow data are not available, but although physically based, there still remain a number of problems in applying these models to ungauged catchments. HYSIM (HYdrograph SImulation Model) documented by Manley (1978), mostly contains physically based parameters, but three groundwater parameters can only be evaluated by hydrograph analysis. These must therefore be estimated from a nearby gauged catchment. WATSIM (WATer SImulation Model) (Aston and Dunin, 1979, 1980; Dunin and Aston, 1981; Aston et al, 1980) contains a parameter describing the storage coefficient for overland flow, which can only be reliably estimated by calibration.

It can be illustrated that many physically based parameters included in models for ungauged catchments do require field measurement studies to be conducted. For example, to gain sufficient accuracy it is necessary that many parameters in TOPMODEL (TOPography MODEL) (Beven and Kirkby, 1976, 1979a, 1979b; Beven, 1977a; Beven et al, 1984) are estimated directly from field measurement. This model requires that convergent flow lines be defined on the basis of topography. However, topographic maps are considered by the authors rarely to provide the required resolution and so their use must be supplemented by aerial photographs and field surveys. Sprinkling infiltrometer tests are necessary to provide information on vegetation and surface storage properties. Channel flow parameters must also be derived from stream velocity measurements. WATSIM requires laboratory experiments to define the suction moisture relation, neutron probe applications to establish the initial moisture content, and infiltrometer ring measurements for saturated hydraulic conductivity measurements.

SPUR (Simulation of Production Utilization of Rangeland model) (Renard et al, 1984) was designed to enable parameter estimation from readily available soils and topography maps. However, this model does contain certain parameters which it might be difficult to estimate from such a minimum amount of data, for example a soil parameter which expresses the degree of cracking and a subsurface return flow travel time parameter. Indeed, Renard et al (1984) in describing the parameter estimation of the return flow coefficient, considered that it would require "Experienced hydrologists familiar with the base flow characteristics of watersheds within a region" (Renard et al, 1984, p23). The ungauged application intended in this thesis does not presuppose that such a detailed familiarization with the catchment is always feasible.

In CREAMS-1 (Chemicals, Runoff and Erosion from Agricultural Management Systems) the hydrological model CDRHM (Creams Daily Rainfall Hydrology Model) contains parameters which are estimated from maps. The newer version of the model CREAMS-2 (Smith, 1983) and SWAM (Small WAtershed Model) (DeCoursey, 1982) which is based on CREAMS-2, contain many more complex relationships, but are still designed for use without calibration. A series of tables and charts are therefore provided to aid parameter estimation where no on-site information is available.

This section has argued therefore that a number of ungauged catchment models do exist but that their examination reveals that:

1 Mathematical hydrological models which contain calibrated parameters are not suitable for application to the ungauged catchment because of their streamflow information requirement. Physically based parameter models may be considered to be more suitable for this application.

2 There are a number of problems associated with the process of model calibration, and even where the necessary streamflow information is available more accurate and reliable models will be derived if they are designed to contain physically realistic parameters.

3 It is not sufficient to design a model which contains physically based parameters, these must also be parameters for which information is likely to exist for the ungauged catchment. It is not always possible to establish a series of field experiments to provide parameter values.

It is also interesting to note that in the literature which addresses the ungauged catchment modelling issue, there exist a number of 'red herrings'. The model proposed by Gupta and Soloman (1977a 1977b), and Soloman and Gupta (1977) to estimate catchment runoff and sediment yield was descibed in their title to be applicable to the ungauged catchment. This model however, requires both measured runoff and sediment discharge data for calibration. It can only be surmised that the model is intended for application to ungauged reaches of a gauged basin.

There is a need therefore to develop a physically based parameter model which will provide flood forecasts for an ungauged catchment and which requires a suitable level of input data.

1.2 Operational requirements

The second criterion which the modified version of HYMO should fulfil is that it should meet certain operational requirements, and these will be discussed in this section. It is considered to be essential that the model should be of a form suitable for practical or routine use as it has been common to ignore operational logistics in modelling exercises. This requirement places certain limitations on the model in terms of the nature of the data which can be referenced, and on the model implementation onto the computer system and programming. These two aspects will be discussed in more detail.

1.2.1 Data restrictions

The quantity and quality of data which the model will have access to have already been restricted by the proposed ungauged application which has been discussed in section 1.1. However a further series of restrictions must now be imposed to ensure a fully operational model.

Firstly, it is important that the data collection stage should not be too time consuming, nor should it require important decisions to be made subjectively by the user. No assumptions can be made about the status or experience of a potential user. Indeed, they may have a technical rather than a professional status, and may not be familiar with either the model operation or its relationship to the catchment. Precise guidelines must be provided for data preparation and parameter estimation.

In the ungauged application of USDAHL-74 to watersheds in the South Great Plains, for example, Nicks et al (1977) illustrated that between 81 and 151 parameters pertaining to watershed zones, flow routing, subsurface flows, and land use are involved. The author claimed that parameter estimation involved a great deal of data preparation, which for large watersheds with many soils and land uses becomes a formidable task in lumping data into single parameter estimates. This effect was reduced significantly by an automatic map digitizing system which both digitizes and calculates parameter values. Table 4 indicates the operational guidelines for parameter estimation of the Stanford Watershed Model (Ross, 1970). In section D there are a number of parameters for which few guidelines for estimation are given. The interflow recession constant and the index controlling the time distribution and quantities of water entering interflow were not estimated in the calibration process because of poor activating data which did not stimulate interflow. It was consequently impossible to explore any correlation relationships involving these two parameters and no method of estimation was provided for them. The streamflow routing parameters were not estimated as a different routing procedure was used in calibration. The factor which estimates the current rate at which swamp vegetation is draining water from below the water table and that which estimates the fraction of moisture entering the ground water which leaves the basin as subsurface flow are recommended to be estimated by trial and error. The only operational guidelines which are given for these are that for most basins, the best fit is provided when these are set to zero. Under these circumstances, parameter estimation is in the hands of the user. Unfamiliarity with the model or catchment clearly inhibits the derivation of appropriate estimates and hence reduces model reliability.

Secondly, as far as possible, techniques should be available to the user which allow parameter estimates to be developed should the necessary information not be accessible (Hannaford and Hall, 1981), and to interpolate values of missing data (Linsley, 1982).

Section 1.1 illustrated that many models are provided with look-up tables in order to allow parameter estimation without calibration. There exists a good deal of soils information in the United States which potentially could be utilized by ungauged catchment applications. Two sources are considered here:

1 The United States Army Corps of Engineers (1983) have developed a data base containing soils information called SIRS (Soil Information

Retreival System) in which information on soil texture, organic matter content, permeability, available water content, and moist bulk density is provided for each soil group. Most numerical values are given as ranges.

2 Rawls et al (1982) have provided a table of soil water and saturated hydraulic conductivity properties of each soil texture group. This has been derived from 1,323 soils from 32 States in North America. All values are given in terms of mean and standard deviation. A number of regression relationships are given which allow the prediction of the moisture content retained at particular suctions for each soil texture class.

There also exists a number of empirical formulae which have been developed to relate soil hydrological characteristics, which are difficult to measure, to more commonly available soil characteristics, such as soil texture. Anderson and Howes (1984), Anderson et al (1985), and Anderson and Howes (inpress) have stressed the value of such formula for hydrological modelling and particularly for the ungauged catchment. Rogowski (1971), Clapp and Hornberger (1978), Gupta and Larson (1979), Ghosh (1980), Arya and Paris (1981), De Jong (1983) have all provided empirical formulae for deriving the suction moisture curve from soil physical properties and perhaps one or two actual measurements of moisture content at specific suctions. Brakensiek and Rawls (1983) presented a series of charts and regression formulae for predicting soil water hydraulic properties, and in particular for deriving the parameters of the Green Ampt infiltration equation, from organic matter and soil texture information.

Examples of the use of these relationships are found in the application of WATSIM to the ungauged catchment. Estimates of suction at the wetting front are required to apply the infiltration model. This is a physically based parameter, but measured values are not likely to be available for the ungauged catchment. For the application, it can be estimated by one of two procedures, which are both claimed to provide similar results (Aston and Dunin, 1979). It can be determined from the suction moisture curve, given the assumption that the average suction is the mean of the suction at initial moisture content and at saturation, and ignoring hysteresis. Alternatively, it can be calculated using an empirical relationship.

In support of the use of empirical formulae for parameter estimation, Engman et al (1981) demonstrated that for an application of KINEROS, a physically based model containing a two paramater infiltration model and a kinematic routing scheme, to a watershed of 4.37 hectares, that the use of infiltration properties derived from soil textural information proved to provide results as successful as those derived from very detailed measured information which is available for this catchment.

1.2.2 Computing and programming implications

An operational model suitable for routine practical application by a user who is not familiar with the design and detail of the model imposes five requirements on the computer implementation of the model.

1 The model chosen must be suitable in terms of its computing requirements for application on a microcomputer system. In the past, the use of mathematical hydrological models was associated with access to a mainframe computer, since these were the only machines which were available with sufficient capacity to run the models. Within the last few years, there has been an increase in the power and efficiency of microcomputers. There has also been an associated decrease in hardware costs, and as Elgy and Elgy (1982) pointed out, the Engineer now has access to the desktop microcomputer, and it may be of interest to capitalize upon this and to develop hydrological models in a package form which can be run directly on such microcomputer systems.

   The hardware of the microcomputer system imposes certain limitations on the physical size of the program and on the number of calculations which can be achieved in an acceptable period of real time. The software available on microcomputer also affects a constraining influence. For example, many complex hydrological models which run on mainframes access mathematical libraries to operate certain complex mathematical solutions. These facilities may not be available on the microcomputer, and consequently more programming is left in the hands of the model builder. More care is needed therefore, in programming and in implementation.

2 The implementation of the hydrological model must be easy for the operator to use. The user cannot be assumed to be familiar with the model, or with the programming techniques which have been used. It is important that input and output should be properly organized. The program may be interactive and provide sophisticated facilities for data entry including editing of incorrectly input data. It should run checks on the data being entered, make corrections where possible, or provide error and warning messages for the operator. A choice of model operations, and of the form of output information should be provided for the user. Clearly, the package must be supported by detailed and clear documentation. An online help facility would be useful.

3 The software must be reliable. Rzevski (1982) addressed the issue of standards for simulation software, and states clearly that there should be a high probability that the software will operate without failure during a specified interval of time. The operation should not deviate under any circumstances from the functional specification, nor should it contain errors or missing statements which will cause error in operation. When the program has been fully cleared of errors, it might be advantageous to include error recovery control structures which will prevent incorrect operations from occuring, the model will hence be fault tolerant.

4 The program code should be written paying attention to programming techniques. For example, adherence to the principles of structured programming (Jackson, 1975) will make it very much easier to debug the final code, and to make later additions and modifications which may not be implementated by the program originator. It is also very

much easier to document a structured program for the use of others. These operational requirements impose a need for a transparent model; one whose model structure, every equation and parameter, and hence its operation should be explainable to and understood by any external user who is unaccustomed to the specific model.

Model implementation in a high level simulation language could be considered. Simulation languages have been written to allow nonlinear partial differential equations to be programmed without familiarity with numerical methods and computer programming. Some examples include CSMP (Continuous Systems Modelling Program) for continuous models (those described by differential equations), GPSS (General Purpose Simulation System) for discrete models (where the state of the system changes at given points in time), and Simscript for combined models. These hold certain advantages for simulation applications over general purpose modelling in that they are often more convenient, transparent, and concise. Source code is shorter and hence easier to assimilate and evaluate. The use of simulation languages can sometimes be more cost effective in that they are less demanding in terms of involvement of the analyst with programming details, and it is easier to commit a simulation model to a computer program. However, as Bratley et al (1983) have stated, when these languages are used, convenience is often traded for control. The resulting simulation model may include behaviour which is neither understood nor predictable.

5 For a model to be used operationally, it is necessary to provide information concerning the potential sources and the magnitude of the errors associated with the model predictions. Hannaford and Hall (1981) pointed out that sufficient information about the general capabilities and limitations of the model together with its operational constraints (and program if necessary) must be provided to the user to enable him or her effectively to apply and interpret model results. This necessitates that the model be fully evaluated and its reliability be established by repeated applications. Model evaluation is considered further in the following section.

It is also important that the model and its implementation should be suitable for real time forecasting applications. The run time for the program must be as rapid as possible.

1.3 Model evaluation

The third criterion which the proposed modified version of HYMO should fulfil is that it should be fully evaluated. This section comments on the role and importance of model evaluation. The problems involved in the design of a model evaluation procedure will be examined, and a three stage strategy of evaluation will be suggested as a suitable methodology. Much of the discussion involves points which are not made specifically in the hydrological literature, but more widely for simulation modelling in other disciplines.

1.3.1 The need for model evaluation

Leimkühler (1982) discussed certain methodological problems in modelling in the context of energy systems. This quotation serves to illustrate some of the major problems which he envisaged and which it is suggested here are also encountered in mathematical hydrological modelling studies.

> "The circumstances are familiar: every time one attends a conference concerned with progress in the modelling business, a number of new or "almost new" models (taking into account the habit of "scientific recycling") with promising features and, hopefully, great explanatory and prognostic or decision-aiding power is presented. The procedures of such a presentation are mutually congruent: in front of experts (or what has to be taken as such) a "model" is announced, and goals and aims of a project for which a model and the use of a model were thought to be of value are shortly mentioned. Then, the model conception is given a

> brief outline, some important structural features are exposed, most of the underlying assumptions are not mentioned, some results are presented, more of them are promised for the not-too-distant future; and under mild applause one modelling expert gives way to another, who proceeds in a most similar manner." (Leimkühler, 1982, p61)

Hydrological models are rarely fully evaluated but the need for this has been emphasized by many, Kisiel and Duckstein (1972), Dooge (1972, 1977, 1981), Amorocho (1973, 1979), Weber et al (1973), Yevjevich (1974), Valdares Tavares (1975), and Dunin (1975). Validation and verification together provide a methodology for establishing the suitability and relevance of a model for a particular application and for assessing the level of confidence associated with the information derived from the model. The provision of this information is considered to be important for three reasons:

1 For the ungauged application, it is necessary to provide the potential user with a reasonable assessment of the reliability of the information provided by the model.

2 It has been demonstrated by Naef (1981) that even a simple hydrological model will predict an increase in stream flow in response to rainfall, and recession after the storm ceases. It is necessary to develop a methodology which establishes the relative standing of these models. Hydrology will not advance if vast numbers of untested model are allowed to accumulate.

> "The fact is however, that in few scientific pursuits have the dangers of poor testing of hypotheses surrounded by so much uncertainty been taken so lightly as in hydrology." (Amorocho, 1973, p932)

3 It is the responsibility of the model designer to clarify and draw attention to the model limitations (Weber et al, 1973). This enables

the user correctly to apply the model and interpret the results. As Frenkiel and Goodall (1978) have stressed, a model should not be considered to be a substitute for thought, but should act merely as an aid to thinking. Failure fully to discuss the model limitations and its consequent application to inappróprate conditions will lead ultimately to a lack of faith in modelling. Snyder and Stall (1965) also have warned that despite the application of numerical methods and the use of computers, the user should not blindly rely upon them. If he "...abdicates much of his responsibility...", then research loses "...the crucial elements of intelligence and logic...", attributes which "...only man can contribute..." (Snyder and Stall, 1965, p99).

1.3.2 Problems involved in the design of a model evaluation procedure

One possible reason for the lack of model evaluation is that there is no commonly accepted methodology as to how the process should be carried out, other than that the procedure must be objective, and applied within the context of the proposed application. It is this which conditions the appropriate level of detail and precision which can be accepted. Van Horn (1971) considered that model evaluation is not a procedure which can be generalized, but is unique to the specific model and application. Gilmour (1973) however, did attempt to provide a more generalized procedure.

In some modelling studies, it is interesting to note that the term validation has been used specifically to refer only to the process of statistically comparing model output to independent historical series. This process has been applied when model formulation has been completed, and all of the data collected. Indeed, the verification and validation of models which has been undertaken for hydrology has traditionally opted for this positivist approach, in which the sole criterion used to determine a valid model is based upon empirical testing. In this analysis, model evaluation is considered to encompass a broader series of techniques which can be applied during model design, and before large resources have been wasted.

Of course it is important to stress that no model of a natural environment system can ever be completely validated. As Beven (1975) pointed out, this is precluded by the presence of uncertainty and equifinality within the prototype system. It is also precluded because inferences concerning model validity must necessarily be made from a small number of experimental frames. A good fit to a data set only establishes a principle of representation to that particular data set. Models make many simplifying assumptions to remain tractable and operational, and as they are therefore neither completely comprehensive nor fully reliable, they will not exactly reproduce the behaviour of the real system. As Kisiel (1971, p 260) remarks:

> "Models are like statistical hypotheses; strictly speaking we do not accept them. We state that there is no basis to reject them."

1.3.3 A three stage model evaluation strategy

A suitable methodology for model evaluation is considered to be a three stage procedure (Sargent, 1982). This is indicated in figure 2.

Mathematical model validation

This is the first stage of model evaluation and refers to the process of establishing the model's face validity. It is basically a subjective procedure aimed at establishing that the assumptions made about the real system by the model are reasonable and that the model adequately reflects the essential features and behaviour of the real system which are relevant to the application in mind. If the model is conceptual, then the assumptions made must be seen to conform to basic scientific principles. This process involves assessments of the model's realism and logical structure to establish that it is internally consistent and that it makes sense. This can be undertaken during model design.

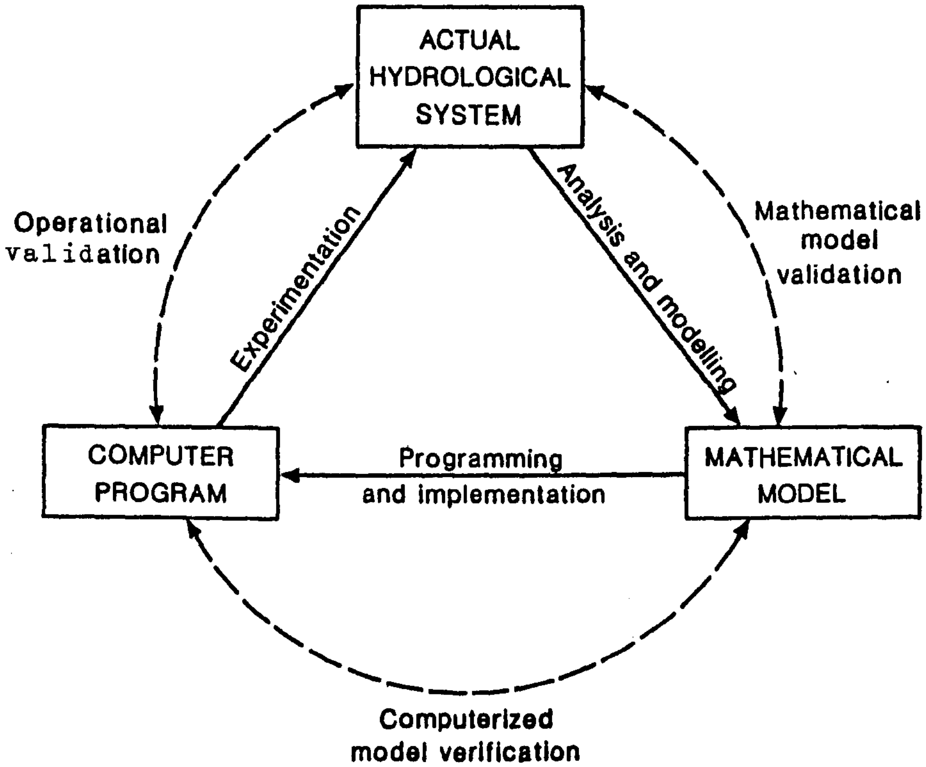


Figure 2: A three stage model evaluation strategy (adapted from Sargent, 1982, figure 2)

Computerized model verification

This involves a series of techniques which are designed to ensure that the computer program actually carries out the logical processes expected of it, that the hydrological processes act rationally and that the program is consistent with the functionality of the mathematical model. The literature suggests several aspects of the program operation which should be checked. It is important for example to demonstrate that if the model inputs are held constant, that over several runs of the model there is no variance of the output. This is referred to by Hermann (1967) as establishing the model's internal validity. It should also be established that the continuity condition is satisfied during operation of the model. Bratley et al (1983) also suggested that at a basic level, results derived from a short computer simulation be compared to the results of a hand calculation. They also suggested that the parameter values should be stressed to indicate whether or not the model provides sensible output for infrequent events or conditions. There are many errors or hidden modes of behaviour in a program which may only appear under stressed conditions. The period of time for which the model remains stable should be established, beyond this point errors may accumulate and predictions become unreasonable. It is also very important to establish whether the model operates satisfactorily for the expected levels of data accuracy. Where the model structure can be questioned and parameters are known only to a given degree of accuracy, it becomes necessary to apply a sensitivity analysis to establish the confidence intervals which can be placed about the information generated by the model. It is also beneficial to explore the model's performance when the assumptions are not met, and to thereby determine the model's sensitivity to its central assumptions.

Operational validation

This final stage serves to establish a measure of the extent to which the model and the program implementing it represent an accurate representation of reality. It is acheived by a comparison of predicted and observed values for a wide range of conditions. There will nearly always be some flood event or basin condition where the model will produce satisfactory results. Discrepencies must however be small for a range of applications. Conditions outside the model's range of application must also be defined.

1.4 Model structure

The fourth criterion which the proposed modified version of HYMO should fulfil is that the most appropriate model structure must be selected. This section is concerned with establishing a philosophical basis for the choice of a suitable mathematical model for the ungauged, operational application. It is considered to be essential that, within the context of the proposed model application, a model must be both hydrologically and logically sound. However, as the following discussion illustrates, it is difficult to establish a methodology which is scientifically satisfactory, but which also remains operationally feasible.

Section 1.1 has already emphasized the importance of physically based parameter models in ungauged catchment applications. However, as Anderson and Howes (in press) point out, physically based parameter models have traditionally been associated with research and scientific efforts rather than with operational applications. This section seeks to illustrate that there are certain elements of physically based parameter models which have potential in operational applications, especially in the context of the ungauged catchment.

Efforts in mathematical hydrological modelling have been concerned with the development of relationships between rainfall and runoff, and can very broadly been divided into two approaches (Amorocho and Hart, 1964; Amorocho, 1979; Beven and O'Connell, 1982): those directed towards scientific advancement and research, and those directed towards practical goals and applications. Figure 3 indicates that although mathematical modelling is associated with both approaches, the role and hence the characteristics of the models are very different. Mathematical hydrological models are associated with both scientific

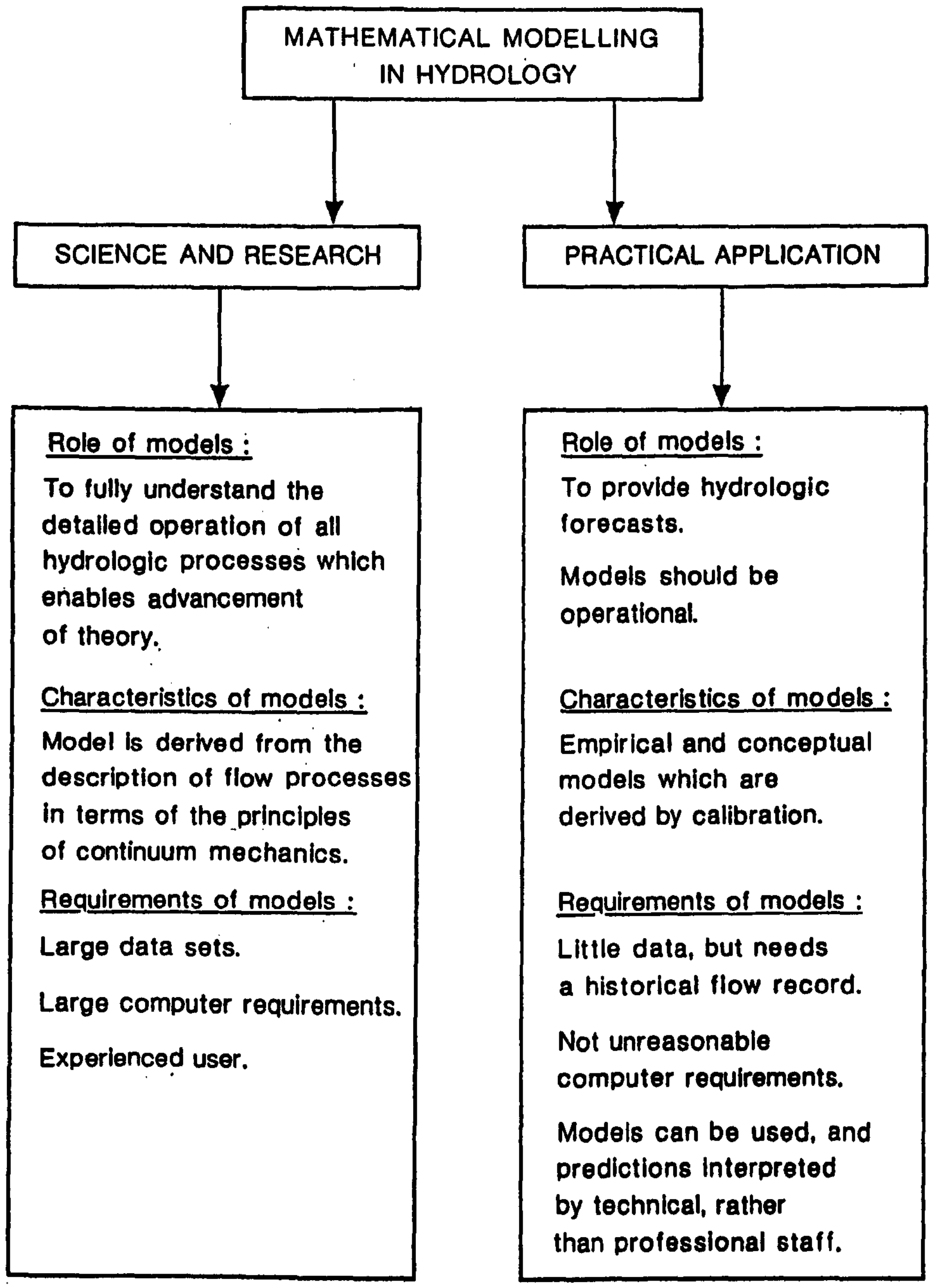


Figure 3 The division of mathematical modelling in hydrology

environments and practical applications. The advantages and disadvantages of these models will be reviewed in this section, and the prospects and recommendations for the infusion of physically based models into practical applications will also be discussed.

1.4.1 Hydrological models in scientific and research environments

Scientific research objectives, the investigation and interpretation of the detailed causal mechanisms of hydrological processes, are achieved by the application of physically based mathematical hydrological models. These describe the water movement within the catchment in terms of the laws of physics. The various types of flow which occur in the catchment, overland, subsurface, and channelized, are described in terms of the principles of continuum mechanics: the conservation of mass, energy, and momentum. The equations which are derived are nonlinear partial differential equations to which numerical solutions are possible for a number of initial and boundary conditions and analytical solutions are possible for certain restricting and hence unrealistic conditions. These models are useful for interpreting and organising field measurements and for examining the causes and behaviour of the various mechanisms of surface and subsurface flow. For example, Freeze (1971) used a three dimensional model of transient saturated and unsaturated flow to provide insight into the development of perched water tables and the areal variation of water table fluctuations. Stephenson and Freeze (1974) applied this model to a further catchment to evaluate the mechanisms of runoff generation from snowmelt. Freeze (1972a, 1972b) also examined those combinations of conditions for which subsurface flow processes operate. Beven (1977b) used a physically based model to examine the sensitivity of subsurface flow to a range of slope conditions.

In 1969, Freeze and Harlan examined the possibility of deriving a rigorous physically based catchment model. They admitted that at that time, there had been insufficient theoretical advancement to permit the construction of the complete mathematical description of the hydrological processes which occur in a catchment, in three dimensions.

They considered however, that there would be progress towards this goal. Today, there are still very many models which concentrate solely on one hydrological process, rather than on the complete catchment. Storm and Jensen (1984) have stressed that it is still not economically feasible to develop a full three-dimensional system.

A number of points have been proposed which argue for the philosophical superiority of physically based models. These models are compatible with our conceptual knowledge of the catchment storm response. As they have physically based parameters, the behaviour of hydrological processes for a given set of variables can be derived without calibration, and they are synonymous with the idea of a unique catchment response. They are considered to have advantages over calibrated models in areas where no historical data are available, or where conditions have not existed before. They have the potential to provide more accurate predictions as the processes are more realistically modelled. They are considered to be widely applicable to a range of conditions.

There are however a number of significant problems with physically based models, even for scientific applications. They have not enjoyed the success in improved predictions which theoretically should have been theirs. This may be due to certain technical problems.

1 Physically based models require a large quantity of catchment data, and their application is often not sufficiently supported by data. Stephenson and Freeze (1974) applied a physically based model to a well instrumented hillslope, and yet they still had to use considerable experience to estimate model parameters. Freeze (1972) developed a model of surface and subsurface flow which uses 30,000 nodes. In the research environment, this degree of data resolution is met with synthetically derived data, but if sufficient data cannot be obtained, the model cannot be fully validated. It may consequently contain hidden modes of behaviour which are uncharacteristic of the system. As McPhearson (1975, p247) has commented:

> "Strident advocates of complex models appear to reason that the application of a larger number of guesses to a larger number of unknowns is somehow better than a smaller number, on the assumption that the more complicated the procedure the better the results."

Furthermore, many of these models have a tendency to be highly sensitive to error in the data.

2 There are problems associated with the numerical solution of these models. Model error is introduced by the choice of numerical method, and the assumptions which are made to keep the solution tractable. Frequently these methods exhibit stability and convergence problems which can only be removed by reducing the space and time discretion to such a small scale that the time for computation becomes impractical. Typically, these models require the capacity of a mainframe computer.

3 Operation of these models demands the detailed knowledge, experience, and familiarity of the user. Clearly, such models could not be described as portable. There are not easily transferable to alternative watersheds because of the data requirements and the prohibitive costs of data collection and preparation.

1.4.2 Hydrological models in practical and operational applications

Models designed to meet practical application goals are restricted to simpler structures due to fundamental data limitations and operational logistics. They comprise both empirical and certain types of conceptual model in which exact replication of the prototype system is not considered to be critical. Klemeš (1982a) has described the process of designing such models as the search for a "hydrologic crystal ball" (Klemeš, 1982a, p96). Empirical, or black box models provide convenient and practical mathematical descriptions of hydrological observations. Conceptual models such as the Stanford Watershed model (Crawford and

Linsley, 1966) and USDAHL-74 (Holtan and Lopez, 1971), are also included in this application category. These models are conceptual in that their structure has a physical basis. The model is divided into subsystems which correspond to the various hydrological components of the prototype. Within each subsystem however, the relationship describing the movement of water is empirical and calibrated. Application of such models requires historical data for calibration. These models are designed specifically for forecasting and prediction and provide little insight into the internal hydrological mechanisms of the watershed, and indeed the implicit ideal of this approach is to find the simplest model which works.

Simple empirical models have certain advantages for applications, and for prediction purposes they are considered to be adequate. Indeed, the improvements gained from increasing the complexity of the model are not always in proportion to the extra effort and work involved. However, for understanding the internal behaviour of the hydrological system, the increased complexity is worthwhile. Many authors have contributed to the debate as to the degree of realism which should be sought in a model, in order to provide the prescribed levels of accuracy. A number of studies (Kirkby, 1975; Pitman, 1978; Naef, 1981) demonstrate the superiority of results derived from simpler, when compared to more complex, models. This has led to a feeling of general satisfaction with empirical models for practical applications. Dooge (1972) captured this feeling when in the context of water resources development he comments that "...a model is something to be used rather than something to be believed..." and that "...individual models must always be regarded as tools which are designed to be useful for a particular purpose, rather than as dogmas which support an ideology" (Dooge, 1972, p172). This feature may be due to the fact that the behaviour of natural systems is heavily dampened. Indeed Body (1975) did not consider that for these applications, procedures such as the unit hydrograph and rational formula will ever be replaced.

However, because of their simplicity, simple empirical models do sacrifice scientific rigour, and run the risk of not fully representing the most important characteristics of the system. As emphasized in section 1.1, these models are only suitable for application to those conditions for which they have been calibrated. Klemeš (1982b) considers that in practical operational applications, the problem of prediction has traditionally been approached as an engineering rather than a hydrological problem. The models which have consequently been produced are of no "hydrologic consequence" (Klemeš, 1982b, p141).

1.4.3 The infusion of physically based models into practical applications

There are those who would insist that physically based models can only be applied in research situations and that they are not appropriate for routine application (Kirkby, 1975; Weisman, 1982). They would argue that the effort which would be involved in setting up the data sources, and in running the model are likely to be too high in relation to improvements which, based on past experience, can be derived in predictions.

As Askew (1974) noted, there has been very little effort directed towards the application of these physically based models to practical applications.

> "While I appreciate that many very complex and sophisticated models have been developed mainly as research tools and as means of studying the land phase of the hydrological cycle, there is an all too frequent tendency to describe as fit for practical application, models which are quite unsuitable because of the complexity, cost of operation, and need for copious data." (Askew, 1974, p1113)

There are those however who advocate the input of research efforts into practical applications. Pattison (1975) and Dunin (1975) have both stressed that scientific models must be aware of and be constrained by practical operational needs. This will not involve merely a straightforward translation of physically based models, but it is suggested that elements of, or generalizations derived from, these models should be considered as useful inputs to the ungauged modelling application.

The potential operational use of physically based models is supported by Dunin (1975), Amerman (1973), Body (1975), Dunne (1982), and Anderson and Howes (in press). These operational models should be in a modified and developed form, such as approximate solutions for the partial differential equations. For example, SWAM (DeCoursey, 1982) although intended for practical application, was designed initially as a complex physically based model which was admitted as being of more value as a research tool. This was progressively and selectively simplified and aggregated in order to produce an operational model.

It is proposed that any model designed for flood forecasting in the ungauged catchment should contain parameters which relate directly to measurable basin characteristics. Physically based models provide the means for allowing this and there are elements of these models which need not be totally confined to a role in scientific enquiry, but which may also serve a useful purpose in practical applications. As Stephenson and Freeze (1974) pointed out, fully distributed models are not suitable for routine application to the ungauged catchment, but it is essential to understand the operation of the system so that simpler models can be more "...firmly based in reality..." (Stephenson and Freeze, 1974, p294).

1.5 Spatial variability

The fifth criterion which the proposed modified version of HYMO should fulfil is that it should take spatial variability into account. There is a good deal of literature in hydrology which details the high degree of temporal and spatial variability of both catchment and precipitation characteristics. This in turn causes spatial and temporal variations in the operation of hydrological processes and is consequently of importance in any consideration of the transformation of rainfall into runoff.

The literature reveals a wide range of experience concerning the influence of such variability upon the catchment hydrological response. For example, the significance of its influence can be demonstrated in part to depend upon the climatic environment. Kirkby (1985), who has been largely concerned with modelling applications in the humid temperate environment, safely assumed that the potential variability of natural behaviour which is related to the fine detail of catchment variability is dampened to a large degree by areal averaging of flow processes. In contrast, Yair and Lavee (1982, 1985), in examination of the highly discontinuous overland flow generation in an arid limestone environment, demonstrated that the very great degree of spatial and temporal variability of runoff is related to the highly variable nature of rainfall and ground surface characteristics.

McCuen (1976) emphasized that in order for a model to respond in a similar manner to that of the real system, it must be formulated to reflect the variability of the system, and its response. Figure 4 lists a number of models which will serve to illustrate a range of methodologies which have been used to incorporate environmental variability within the model structure, and to evaluate its influence upon hydrological processes. At one extreme, lumped models which are mostly empirical in nature, do not take variability into account. The catchment is regarded as a structureless unit. Some of these models have been developed into semi-lumped models, which enable the whole catchment to be subdivided into smaller units where the assumption of homogeneity may assume more relevance. Where variability is taken into account in the modelling process, two methods have been adopted. Variability may be incorporated into the model deterministically or stochastically. Geometrically distributed models are physically based and are so demanding of data and computer resurces, that a more simplified subset of models which are classified as semi-distributed have been developed. These groups of models, indicated in figure 4, are now discussed.

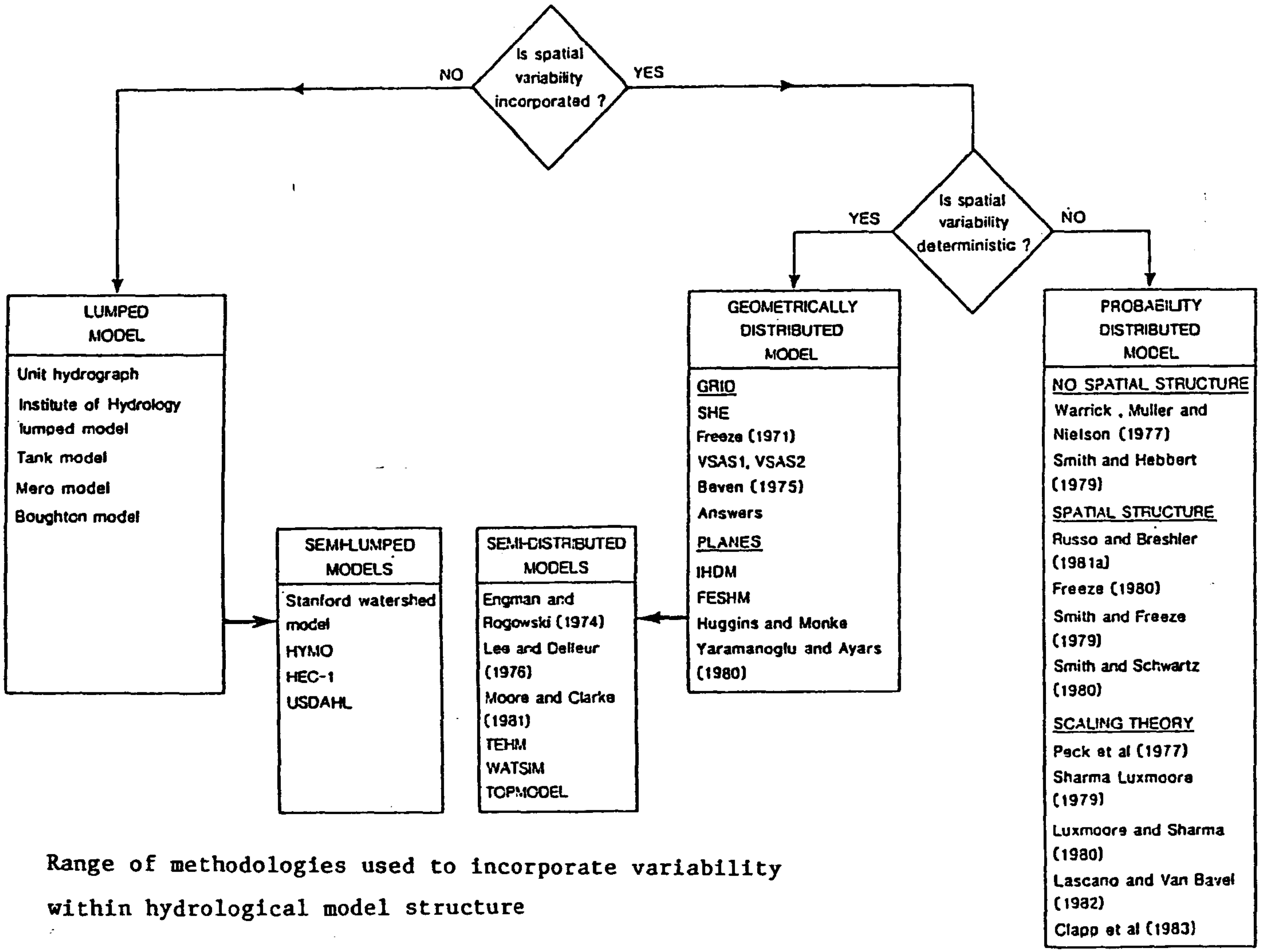


Figure 4 Range of methodologies used to incorporate variability within hydrological model structure

1.5.1 Lumped models

A selection of lumped mathematical hydrological models is provided in figure 4. They assume that streamflow is generated by processes which operate uniformly over the whole catchment area. Model parameters are not physically based, but represent spatial averages. Calibration is therefore required to secure suitable parameter estimates. These models all take advantage of simple empirical formulae, although the model structure may be conceptual.

Examples include unit hydrograph methods, the Institute of Hydrology Lumped Model (Nash and Sutcliffe, 1970), the Tank model (Sugawara, 1961), the MERO model (Mero, 1969), and the Boughton model (Broughton, 1968).

These models are all based on the assumption that the catchment acts to dampen the natural variability (Engman et al, 1971; Amorocho, 1979; and Kirkby, 1985). Practical experience has demonstrated that the performance of these models is indeed adequate for a wide range of catchment conditions. Engman et al (1981), in an application of the KINEROS model, demonstrated that lumped parameter estimates of infiltration parameters provided more accurate predictions than those provided by spatially distributing the parameters. The success of lumped models depends on the stability of the catchment system (Blackie and Eeles, 1985), and although expedient, there exists a high probability of the model not replicating the behaviour of the prototype (McCuen, 1976; Huggins et al, 1973).

Certain semi-lumped catchment models have been developed which allow the whole catchment to be broken down into subunits, thus allowing some degree of variability within a catchment to be incorporated into the model. Within these smaller units, homogeneity is assumed. The manner in which models like the Stanford Watershed Model, HYMO, HEC-1, and USDAHL incorporate variability is illustrated in figure 5. In figure 5 the catchment is subdivided into 5 subunits based on topography, soils, vegetation and hydrological behaviour. The flow diagram illustrates how

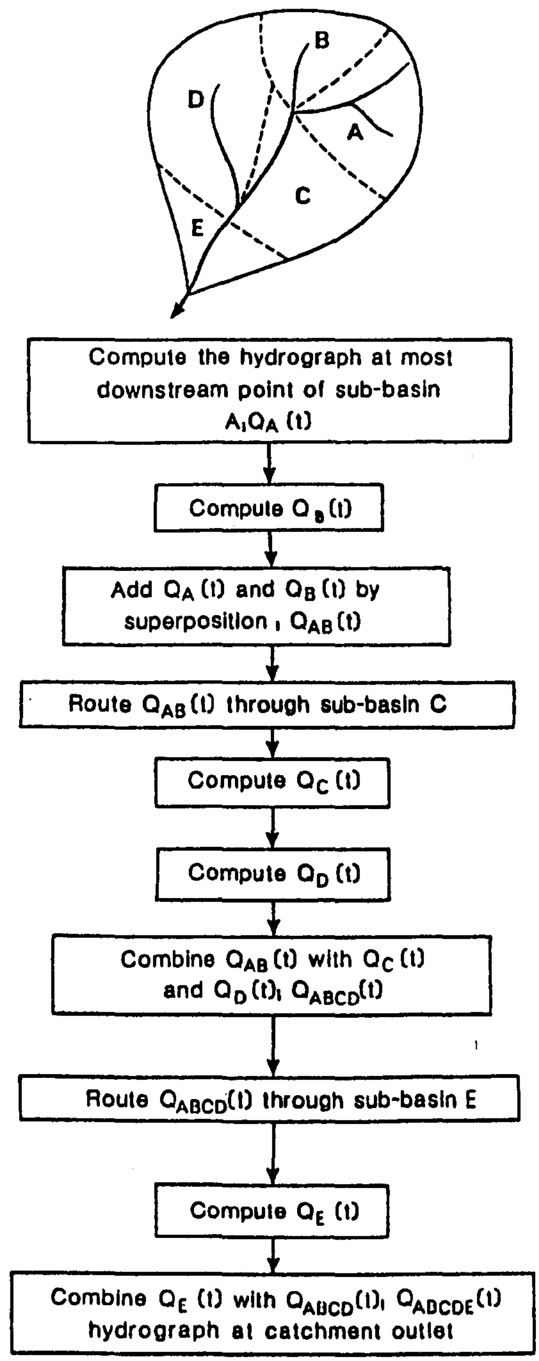


Figure 5: The generation of hydrographs by semi-lumped hydrological models such as HYMO

the hydrographs for each area are generated and cumulated progressing downstream. These models remain simple and conceptual.

1.5.2 Probability distributed models

Many authors have provided evidence of the variability of soil characteristics. Their major findings can be summarized as follows:

1 There is a large amount of variability contained within a mapped soil series. Hills and Reynolds (1969) stressed that the Soil Survey of England and Wales may take as few as 1 or 2 profiles to characterize a series. Rogowski (1972) examined the variability of soil series in the United States, and discovered for example that the moisture content at 15 bars suction varies by 7% for the Houston Black, but by as much as 63% for the Northeast soil series. He attributes this within-series variability to changes in slope, stoniness, depth to bedrock, and the fact that any soil series can contain up to 15% of another unit. Baker (1978) also examined this within-soil series variabilty and emphasized that there is a variation in the ability of the soil to conduct water. This has important implications for the use of soil series data in hydrological modelling.

2 There is also a large degree of variability in a seemingly uniform area, that is a plot which appears to be homogeneous in terms of its relief, aspect, and vegetation cover (Clapp et al, 1983), and indeed would be treated as a homogeneous unit by a hydrological model. Nielsen et al (1973) found that in an area where the soil bulk density and particle size distribution did not vary to any large degree, the steady infiltration rate ranged from 0.5 to 45.7 cm per day. This variability has been referred to in the literature as the soil's inherent variability (Bell at al, 1980). Price and Bauer (1984) studied a slope profile of 5 metre length and 2.5 metre depth and demonstrated that even small, gradual, textural changes can induce significant changes in soil water movement. Hjelmfelt and Burwell (1984) have demonstrated significant runoff variability over an area of Mexico silt loam, which has uniform management treatment.

This variability can not be related to any quantifiable variation of soil surface properties, and furthermore, individual plots within the area do not respond consistently through the sequence of events.

3 The magnitude of variability has often been related to the scale which is being considered. Beckett and Webster (1971) found the amount of variation to increase as the area sampled increases. However, between 50% and 75% of the total variation within a field is already present in any 1 square metre. Hills and Reynolds (1969) found little change in variation with scale, but they do find that a greater variation is associated with a smaller sample size. Coelho (1974) finds that the variation within a field is greater than that between soils. The soil is considered to exhibit macro-uniformity.

4 The magnitude of variability is related to soil properties. Warrick and Nielsen (1980) have provided a convenient summary of the degree of variability of various soil properties. Those properties which exhibit low variability (coefficient of variation of between 6.8% and 11%) include bulk density and saturated moisture content. The particle size distribution and soil moisture characteristics exhibit medium variation of between 20% and 50%, and saturated hydraulic conductivity and the diffusivity coefficient range upwards from 300% variability.

5 The magnitude of variability has been related to depth. Coelho (1974) and Nielsen et al (1983) found variability to increase with depth. In comparison, Cameron (1978) found the surface to be more variable. Hills and Reynolds (1960) stressed that variability does not depend on depth, but that it is related to the soil moisture level. When the soil is either very wet or very dry, variability is low; variability is greatest between these extremes.

6 It is important to appreciate that the degree and nature of variability itself changes with time.

Burrough (1983a, 1983b, 1983c) drew attention to the complexity of the spatial structure of soil variability. The nature of this variability is very complex since very many causes and scales of variability are present. He describes the variation by use of the concept of fractals (Mandelbrot, 1977). Variability is measured by the parameter ′D′, the fractional dimension. The very high value which is derived for soil variability, when compared for example to that for river discharge, indicates the presence of many closely spaced and nested scales of variation occuring over short distances. ′D′ is estimated from the semivariogram and thus a high value indicates the juxtaposition of large positive and large negative correlations. This is attributed to short range changes and the different, but interacting scales of the factors causing variability.

Variability of the soil is related to deterministic factors such as the physical processes of soil formation, but it may also contain stochastic elements. Another important component of variability is stressed by Bouma (1983) and by Smith and Pratt (1984), who drew attention to the role of experimental error and choice of the appropriate measurement technique in contributing to variability, or error.

Several authors have attempted to incorporate measures of this combined variability and error into model structure, and to establish its consequence upon hydrological behaviour. These studies can be divided into three groups according to the manner in which field variability has been expressed. Measures of variability include the use of conventional statistics, geostatistics, and scaling theory. These are now discussed.

Conventional statistics

Measured field variability has traditionally been described by a probability density function which defines the probability of all possible outcomes, a mean which describes the average property, and a standard deviation which describes the dispersion about the mean. The coefficient of variability is used to express variability in a dimensionless form, thus allowing for comparisons to be made. Table 5

Table 5: Probability density functions for a number of soil hydrological parameters

Probability density function		Source
Soil water diffusivity		
Log-normal		Nielsen et al (1973)
Soptivity		
Normal		Russo and Bresler (1981b)
Particle size distribution		
Clay and sand	normal	Nielsen et al (1973)
Silt	normal	Coelho (1974)
Clay	bi-modal	Coelho (1974)
Pore size distribution		
Log-normal		Russo and Bresler (1981b)
Soil moisture characteristic		
Normal		Nielsen et al (1973)
Normal		Russo and Bresler (1981b)
Hydraulic conductivity		
Log-normal		Nielsen et al (1973)
Log-normal		Rogowski (1972)
Log-normal		Baker (1978)
Log-normal		Russo and Bresler (1981b)
Log-normal		Coelho (1974)
Log-normal		Keisling et al (1977)
Soil water content		
Normal		Nielsen et al (1973)
Normal		Russo and Bresler (1981b)
Normal		Hills and Reynolds (1969)
Normal		Bell et al (1980)
Infiltration rates		
Normal		Vieira et al (1981)
Normal		Sisson and Wierenga (1981)
Soil bulk density		
Normal		Nielsen et al (1973)
Normal		Rogowski (1972)
Normal		Cassel and Bauer (1975)
Normal		Coelho (1974)

illustrates the probability functions which have been derived by field measurement programmes for a number of soil properties.

Warrick et al (1977) examined the effect of spatial variability of soil parameters on the distribution of soil water flux over space. They used a Monte Carlo simulation procedure; the soil properties were randomly selected from their respective probability density function according to a given mean and standard deviation. The model is then executed repeatedly and the results stored. A distribution of probable outcomes is produced. These repeated calculatons correspond to repeated field measurement. Smith and Hebbert (1979) also used the Monte Carlo simulation method and found that by incorporating measured variability into the model, runoff occurs earlier and increases more gradually than were uniform conditions to be assumed. They did stress however, that soil properties are not spatially independent and that deterministic spatial variation will have an effect upon hydrological response.

Geostatistics

The conventional statistical approach treats the observations of a property as being statistically independent, and disregards spatial structure. As Russo and Bresler (1981b) stressed, soil properties are not disorganized in space and a more complicated statistical description must be used which incorporates some measure of this spatial dependence. The geostatistics which have been used to describe the spatial structure of soil properties have included spatial autocorrelation, cross correlation, and semivariograms. However, there have been notably fewer field programmes which have attempted to examine the nature of this spatial structure.

Vieira et al (1981) produced a series of semivariograms and autocorrelograms which describe the variability of infiltration rates on a plot of Yolo Loam. They found samples to be correlated within 50 metres. Gajem et al (1981) demonstrated the spatial structure of the physical properties of Pima Clay Loam. Sisson and Wierenga (1981) demonstrated autocorrelation in steady state infiltration rates. Russo and Bresler (1981b) examined autocorrelation in six soil properties. They derived the integral scale, which is the largest distance over which the soil property is autocorrelated. Saturated hydraulic conductivity was found to have an integral scale of 21 metres, water entry value of 44 metres, saturated soil water content of 55 metres, residual soil water content of 25 metres, and sorptivity of 35 metres. Burrough (1983a, 1983b, 1983c) also produced semivariograms for a range of soils.

A number of deterministic models have stochastically incorporated a measure of the spatial structure of variability. Russo and Bresler (1981a) found that spatial structure did have a significant effect on hydrological behaviour in the area of the wetting front, but not at the surface. Freeze (1980) used cross correlation properties between parameters to generate a multivariate stochastic process.

Scaling theory

Scaling theory is a method of describing heterogeneity, based on the concept of similar media, which was introduced by Miller and Miller (1955a, 1955b, 1956) and recently reviewed by Miller (1980). It applies to media which are exactly alike geometrically, but which are different in scale. The media bear the same relationship to each other as do similar triangles. Such similar media, differing only in scale, will have identical porosities and the same particle and pore size distribution. The theory assumes that the media are homogeneous, isotropic and rigid, that the air pressure is constant, that the properties of the liquid are uniform throughout the flow system, and that no isolated drops of water or air bubbles occur. Figure 6 taken from Miller (1980) and the following explanation, help to illustrate this concept.

The soils illustrated in figure 6 may be considered to be similar media. They have identical porosities, but different characteristic lengths (λ). The characteristic length may be the length of a particle or a pore, or an aggregate of an average value of these parameters. The

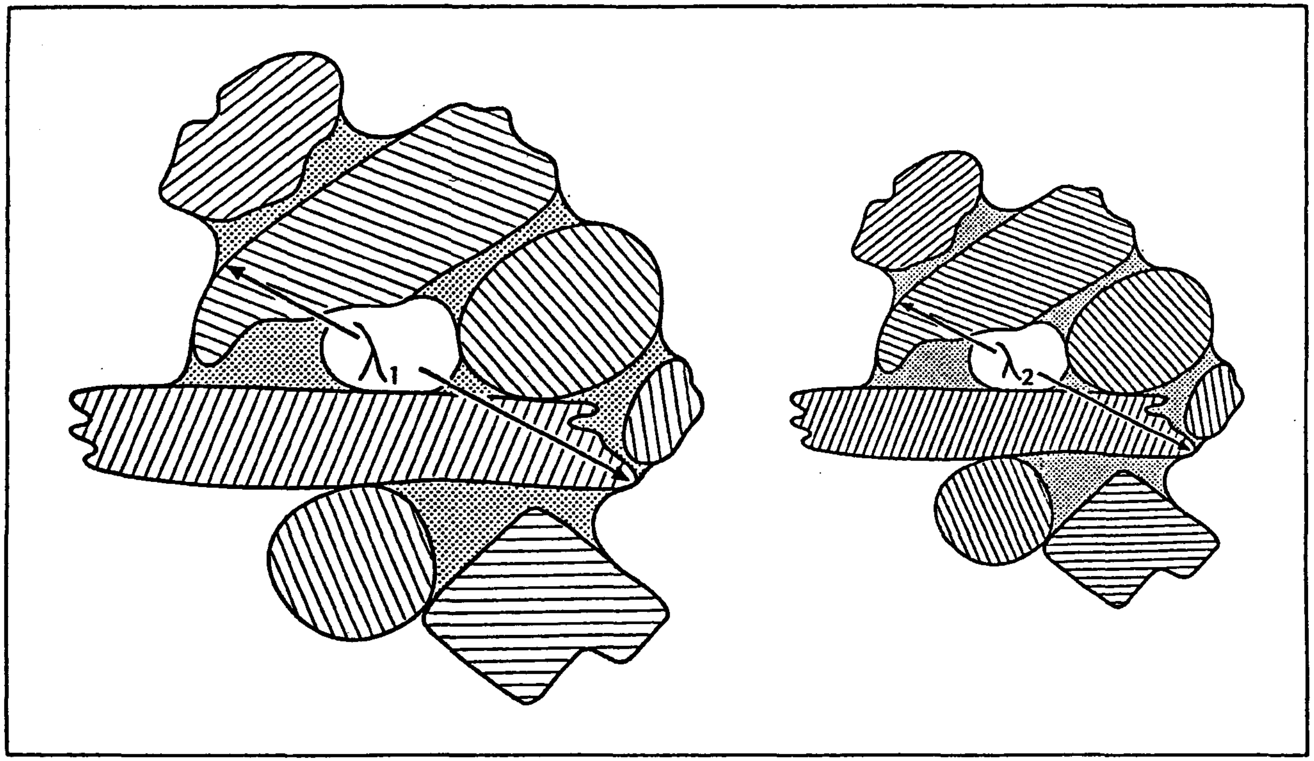


Figure 6 Illustration of two similar media (from Miller, 1980, figure 12.1)

dimensionless scaling coefficient (α) can be defined as the ratio of the characteristic length of a particular soil (λ_i) to that of the reference soil (λ_r). Thus for a soil at location i, the scaling coefficient (α_i) is given by:

$$\alpha_i = \lambda_i / \lambda_r \tag{1}$$

Similarly, for location j:

$$\alpha_j = \lambda_j / \lambda_r \tag{2}$$

The scaling coefficient can then be used to approximate the heterogeneity of various soil hydrological characteristics from location to location over the watershed. These properties are defined from the properties of the reference soil and the distribution of the dimensionless scaling coefficient.

The validity of scaling the soil moisture characteristic curve and conductivity relation is now well established for clean sands (Miller and Miller, 1956; Klute and Wilkinson, 1958; and Elrick et al, 1959). Perfect similar media conditions are not met in field situations, and application to such conditions has received very little attention. Warrick et al (1977) have documented one of the few attempts to determine the validity of the application of scaling concepts to field data and concluded that soil heterogeneity could be approximated quite well by a single scaling factor.

For a given soil moisture content at location i, the soil moisture characteristic ($\Psi_i(\theta)$) and the hydraulic conductivity function ($K_i(\theta)$) are related to the soil moisture characteristic and the hydraulic conductivity function of the reference soil, ($\Psi_r(\theta)$) and ($K_r(\theta)$) respectively, in the following manner:

$$\Psi_i(\theta) = \Psi_r(\theta)/\alpha_i \tag{3}$$

$$K_i(\theta) = K_r(\theta)\alpha_i^2 \tag{4}$$

Where:

Ψ - capilliary potential (metres)
K - hydraulic conductivity ($m\ s^{-1}$)
θ - soil moisture content ($m^3\ m^{-3}$)

Similarly, for location j:

$$\Psi_j(\theta) = \Psi_r(\theta)/\alpha_j \tag{5}$$

$$K_j(\theta) = K_r(\theta)\alpha_j^2 \tag{6}$$

To characterize the variability of a soil over the catchment area therefore, the probability density function, mean, and standard deviation of the dimensionless scaling coefficient are required. Peck et al (1977) assumed this to have a normal distribution with a mean of 1.0 and a coefficient of variation of 25%. However, Warrick et al (1977), Simmons et al (1979) and Warrick and Nielsen (1980) found field measurements to be log-normally distributed. Examples of typical means and standard deviations are given in Warrick et al (1977), who in an analysis of soils field data collected by Nielsen et al (1973) and Coelho (1974) found the Panoche soil to have a mean of 1.0 and a coefficient of variation of between 55% and 170%, the Pima soil a mean of 1.0 and a cofficient of variation variation of 48%, and the Teller soil a mean of 1.0 and a coefficient of variation of 139%.

The characteristics of the dimensionless scaling coefficient therefore characterize the spatial variability in the area. Given the mean soil characteristics of the reference soil, spatial variability of a catchment can be estimated from the distribution of the scaling factor.

Sharma et al (1980) demonstrated that infiltration data, measured at several sites, can be scaled according to similar media concepts. The spatial variation of infiltration can thus be characterized by the variation and distribution of a single dimensionless scaling factor.

There have been a number of studies which have used scaling theory in modelling exercises to determine the implications of variability of soil properties for the operation of hydrological processes.

Peck et al (1977) used scaling theory to determine the effects of variability of hydraulic properties in the Fullerton soil series on water budget components of a forested watershed. They determined that drainage is more sensitive to variation of soil properties than to any other factor. For April, the amount of drainage assuming uniformity was 58.3 mm and this was reduced to 57.6 mm when variability was assumed. This is not a great difference, but the authors assumed the dimensionless scaling coefficient to have a normal distribution with a mean of 1.0 and coefficient of variation of 25%. Later studies (Warrick et al, 1977; Sharma and Luxmoore, 1979) considered 25% to be a considerable underestimate, and themselves assumed a value of at least 50%. Sharma and Luxmoore (1979) also explored the implications of the selection of probability density function, and found that the normal distribution provided 30% to several hundred per cent higher runoff than the log-normal. The higher coefficient of variation also provides significantly different predictions, and the effects of variability are seen to be amplified when rainfall is high.

Luxmoore and Sharma (1980) found that by using scaling to represent variability, predictions of drainage and runoff more closely approximate the measured values. Lascano and Van Bavel (1982) determined that spatial variability of soil properties as described by scaling theory caused a high variation of surface water contents. Clapp et al (1983) found that 75% of variability of soil water after a storm can be explained by soil heterogeneity as represented through scaling theory. They conclude that scaling theory and Monte Carlo simulation together provide an appropriate mathematical method for investigating the effects on model predictions of all sources of soil moisture variability at a field scale.

Three methods have been described by which catchment variability can be described and incorporated into probability distributed models. The basis of probability distributed models is that it is the variation of soil hydrological properties which dominates the hydrological response. It is important however to determine the magnitude and extent of the influence of precipitation, vegetation, and topography on hydrological behaviour.

A modelling exercise conducted by Huggins et al (1973) demonstrated that the relative physical location of parameters within a catchment significantly influenced the hydrograph response of overland flow. Using a physically based model, for a hillslope where a soil with higher infiltration characteristics is located upslope from one with lower infiltration, they indicated that there is more runoff than where the higher infiltration soil is located in the lower slope areas. This latter configuration enables more surface water to infiltrate before it reaches the outlet. Consequently, some models include a geometrically distributed structure and consider the deterministic variation of catchment properties.

1.5.3 Geometrically distributed models

These models are physically based and represent an attempt to attain a complete three dimensional deterministic description for the catchment. One of the major problems in applying the equations of flow processes as described by the principles of physics is the spatial variation of the soils' hydrological properties. Philip (1969, 1975) discussed the success of the micro-hydrologist in describing the behaviour of soils for simplified and homogeneous conditions, compared to the problems faced by the macro-hydrologist who is concerned with the application of such descriptions of flow to the larger scale catchment, for more complex and varied situations. Indeed, Flemming and Smiles (1975) remark that soil physicists have now well developed the infiltration theory for many initial and boundary conditions. Due to the variability of catchment and precipitation conditions, there is a need for physical theory to be developed and validated for more complex situations (Youngs, 1983). There is also a need to determine parameter values which are in some sense meaningful and representative of conditions at a catchment scale.

Physically based models have attempted to incorporate variability into the model structure by dividing the catchment into smaller units and allowing model parameters and input drivers to assume different values according to deterministic variability in the field. The flow equations are solved for each unit, which is internally assumed to be uniform. The response of each unit is then cumulated for the catchment area. These models do allow for the spatial and temporal variation of precipitation characteristics to be incorporated into the model. There have been a number of mathematical modelling exercises which have indicated the significance of this on the streamflow hydrograph. For example, Huff (1967), found variability of precipitation to be especially significant during heavy storms. Dawdy and Bergman (1969) demonstrated that use of a single, lumped estimate of rainfall over a catchment of 25.12 square km provides an estimate of peak discharge with a standard error of 20%. Wilson et al (1979) illustrated that the spatial distribution of a frontal storm significantly affects the catchment outflow of a 68.6 square km area, and Amorocho and Morgan (1971) stressed that small basins do not filter out the spatial charcateristics of variable storm, whereas, in larger catchments channel storage acts as a filter. Beven and Hornberger (1982) demonstrated that it is the timing of peak flow in particular which is affected by spatial and temporal variability of precipitation. In many cases, there is insufficient detail of the variability provided by rain gauges, and for these situations, simulation models can be used to generate both external and internal storm characteristics over space.

Clearly, these geometrically distributed models provide the capability to incorporate the spatially distributed nature of input data, and also the capability to model and predict the variation in types and intensity of processes. Beven and O'Connell (1982) stressed the potential of such models in the assessment of the effects of local land use changes, in the investigation of the effects of spatial variability of inputs, and in the establishment of the movements of pollutants and sediments.

Geometrically distributed models can be classified according to their method for spatially representing the watershed. The aim in this is to maintain as far as possible the flow pattern and spatial character of the prototype. The most complex and demanding models impose a grid upon the catchment, more simplified models assume a series of cascading planes. Several examples of these models are provided in figure 4.

A number of problems, however, can be identified with these models:

1 The subdivision of the catchment into cells or planes demands that a large amount of catchment data be available for parameter estimation. For example, SHE (Système Hydrologique Européen) is a fully geometrically distributed and physically based parameter model which has been developed jointly by the Institute of Hydrology (Great Britain), SOGREAH (France), and the Danish Hydraulic Institute. When SHE was applied to the Wye catchment (Storm and Jensen, 1984; and Bathurst, submitted paper) the catchment area (10.5 square km) was subdivided into 169 grid squares. For each cell in the grid, information for all those parameters indicated in table 6 are required. For each cell, 39 nodes are established in the vertical plane. Although the parameters in table 6 are all theoretically measurable in the field, in practice even for a fully instrumented catchment, this amount of data will not be available. Parameter estimation at best involves the transfer of parameters from measured sites, or at worst the general use of parameter values derived from the literature.

Table 6: Model parameters required for each cell or channel link in the SHE model
(adapted from Bathurst, submitted paper, table 1)

Model component	Parameter
Frame	Ground surface elevation Impermeable bed elevation Distribution codes for rainfall and meterological source stations Soil and vegetation types
Evapotranspiration and interception	Vegetation aerodynamic resistance Vegetation canopy resistance Canopy storage capacity Root distribution with depth Meteorological and precipitation data
Unsaturated flow	Suction moisture curve for each soil layer Soil saturated conductivity for vertical flow
Saturated flow	Conductivity for horizontal flow in direction of each axis Initial phreatic surface level Pumping and recharge data
Overland and channel flow	Initial water surface elevation Overland flow resistance coefficient in direction of each axis Channel flow resistance coefficient Channel width/water surface elevation relationship
Snowmelt	Inital snowpack depth Degree-day factor Initial snow temperature Meteorological and precipitation data

One of the only examples of a fully three dimensional model is that provided by Freeze (1971) for transient saturated and unsaturated flow. The program could accomodate up to 30,000 nodes, which limits the basin area to a few square kilometres, and 300 metres depth. Freeze stressed that the model could potentially accomodate nonhomogeneous and anistropic characteristics, but that the necessary information is not always available. Indeed, Stephenson and Freeze (1974) who document an application of this model stressed that variability in hydraulic conductivity can not be investigated due to a lack of information. These authors applied the model to a heavily instrumented catchment, but even here could not derive enough information to reflect the variability.

2 The parameter values which are selected, although refering to measurable characteristics, must take on values which are representative of the cell or plane. The definition of these appropriate values is currently achieved by calibration. The problems associated with calibration have already been discussed, but it is important to stress that where these very complex, distributed models are concerned, the problems are amplified by the large number of parameters and their interdependence. Automatic calibration techniques cannot be used.

3 A good deal of computer time is required by these models to effect the solution of the flow equations for such small areas.

4 The application of these models requires a good deal of operator experience of the model and catchment.

Due to the intractability of fully distributed models, their application is confined to research environments. The need for practical application has led to the development of semi-distributed models. These aim to integrate the important effects of spatial variation which are derived from application of the fully distributed model, with the data and computer saving attributes of the lumped models. Thus simpler models can be derived by aggregation from the more complex.

Examples of these models are provided in figure 4. Engman and Rogowski (1974) simplified the situation by only considering Hortonian overland flow. A dynamic contributing area, where rainfall intensity exceeds infiltration capacity, is incorporated into the model structure. The catchment is subdivided by soil series. Lee and Delleur (1976) also developed a simple and conceptual model of the contributing area. Moore and Clarke (1981) presented a storage model in which a single store is replaced by a statistical population of stores. These stores can be visualized as narrow, vertical tubes of varying lengths which are closed at the bottom, and open at the top. Rain falling on tube will be stored until the tube is full, the excess then becomes runoff. Contents may be depleted by evaporation. Consequently, the catchment area contributing to runoff is allowed to vary. TEHM (Terrestrial Ecosystem Hydrology Model) contains a coefficient which increases the hydrological response as a function of the potential source area. WATSIM contains a catchment water balance model which can be either distributed or lumped. It is distributed in the sense that it divides the catchment into three domains, which are similar in terms of hydrological behaviour, slope, soil depth and topography. Dunin and Aston (1980) found the distributed version of the model to be superior to the lumped, although the differences between them become less as the time scale increases and overall catchment wetness increases. TOPMODEL simplifies the dynamic variation of saturated areas over the catchment and incorporates the distributed effects in the framework of a more lumped model.

1.6 Summary

A need has been identified to develop a mathematical hydrological model which can provide a flood forecast, but which in addition is applicable to the ungauged catchment, meets operational requirements, is fully evaluated, contains an appropriate model structure, and considers spatial varibility. It is proposed that the development of a modified version of a currently used mathematical hydrological model, HYMO, is to be organized specifically to meet these five requirements. The following recomendations are therefore to be made:

1 The proposed modified HYMO, which is intended for application to the ungauged catchment, will contain physically based, rather than calibrated parameters. Furthermore, as emphasized in section 1.1, for an ungauged application in which no field measurement programme is envisaged, these physically based parameters will be those for which readily accessible or published information is available.

2 To ensure that the proposed modified HYMO meets the operational requirements which were discussed in section 1.2, precise guidelines for parameter estimation will be provided for the user, and techniques will be available to estimate parameters in the situation where the necessary information is not available. In addition, the model software will be of a form suitable to run on a microcomputer system, it will be easy to use, and it is essential that it be reliable. It is useful for future modifications that the code be written in a structured and logical form.

3 The proposed modified HYMO will be fully evaluated. There will be a well considered and thorough assessment of the level of confidence which can be placed on the information which is to be derived from the model. The model limitations will be clearly defined. The three stage model evaluation strategy which has been suggested in section 1.3 will be utilized. This aims to establish the model's face validity, the computer program's internal validity, and the operational validity of the model.

4 The structure which will be selected for the proposed modified HYMO will seek to attain a balance between satisfying scientific and operational objectives. As emphasized in section 1.4, it is not accepted that empirical models provide the only means of practical model application. Within the context of the ungauged application, these are not regarded as suitable, and they are certainly not hydrologically sound. It is to be emphasized that certain elements of physically based models do provide suitable alternatives for operational, application requirements.

5 The proposed modified HYMO will not ignore the spatial variation in the natural environmental system. A measure of the spatial variation of catchment characteristic will be incorporated into the model to assess its impact upon hydrological behaviour. As indicated in section 1.5, a choice will have to be made between probability distributed and semi-distributed models, in the context of operational and ungauged application.

An outline of HYMO, the identification of areas which require improvement, and the development and modifications which have been undertaken (and which proceed directly from recommendations 1, 2, 4, and 5), will be provided in chapter 2. The modified version of HYMO, hereafter referred to as HYMO2, will then be fully evaluated according to recommendation 3. Chapters 3, 4, and 5 provide the details of the three stage model evaluation strategy which is illustrated in figure 2. Chapter 6 provides the details and the implications of a number of further applications of HYMO2. Chapter 7 presents a series of comparisons of the original HYMO and HYMO2. This establishes that in consideration of these five recommendations, improvements to several aspects of the model have been achieved. To conclude, chapter 8 provides a discussion which summarizes the major points which are raised in this thesis, and the recommendations which can be made for future contributions to mathematical hydrological modelling.

2

Development of the proposed mathematical model of catchment hydrology: HYMO2

This chapter examines the structure of HYMO (HYdrograph MOdel, Williams and Hann 1972, 1973) and documents the development and modification of this model according to the recommendations which have been made in section 1.6. HYMO is an event flood hydrograph simulation model, it is a perspicuous model which is easy for a nonprofessional hydrologist to understand and to use, and its data requirements are such that it is suitable for application to the ungauged catchment. A detailed description of HYMO is provided in section 2.1. In application however, it has been demonstrated that HYMO can provide inaccurate and inconsistent predictions, and in particular this irregular performance has been associated with structural deficiencies in the empirical curve number model (United States Department of Agriculture, Soil Conservation Service, 1972) which the model references to generate catchment runoff. The unsuitability of the curve number procedure for this particular application is outlined in section 2.2, and a series of alternative infiltration models are discussed in section 2.3. The replacement model which has been selected for the modification of HYMO, a physically based infiltration model, is developed in section 2.4. This infiltration model has the capability to include the effects of catchment spatial variability by a stochastic methodology.

The newly configured and fully operational model, HYMO2, is presented in section 2.5, which although developed on a mainframe (Honeywell 6800 under Multics) is also able to operate successfully on a 32 bit microcomputer (Hewlett Packard 9816). The results of an extensive model evaluation of HYMO2 are provided in the following chapters.

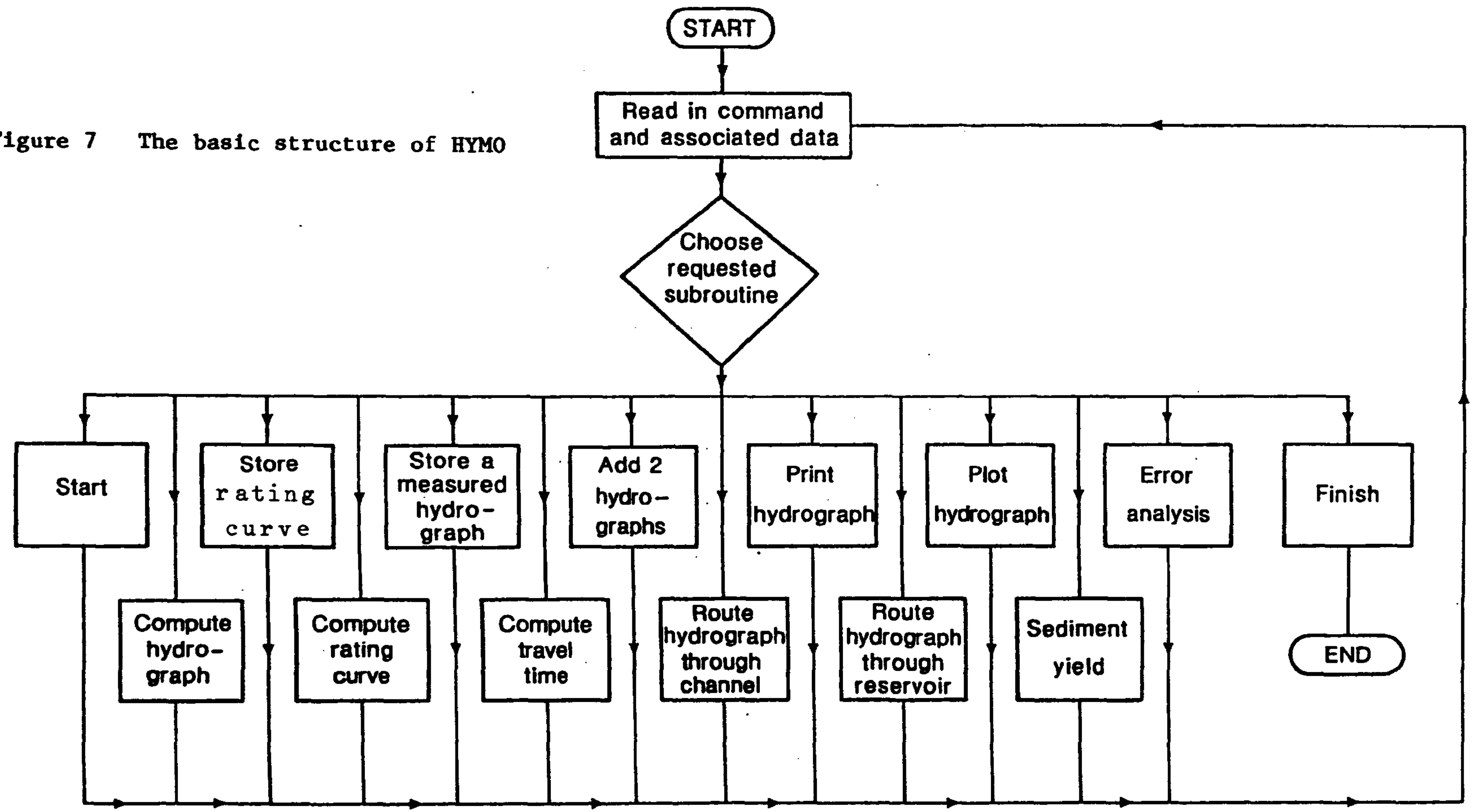
Every effort has been made to keep the notation of the equations presented in this thesis consistent between chapters. Symbols are defined when they are first used and are assumed to retain the same meaning unless otherwise indicated. However, the reader's attention should be drawn to the units which are employed. The mathematical definition of HYMO (section 2.1) and the curve number model (section 2.2) have been developed in the United States and consequently, imperial units have been employed. To maintain the original form of these equations, imperial units have also been presented in sections 2.1 and 2.2 (equations 7 to 37). The mathematical definition of the physically based infiltration model which has been undertaken as part of this thesis, is presented in section 2.4 (equations 38 to 54), in metric units.

2.1 HYMO

HYMO was developed for the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) to estimate surface runoff and soil loss associated with a storm event, for agricultural watersheds. It has been designed specifically for routine application to the ungauged catchment; it requires generally available data and is simple for a user to operate and understand. It is a semi-lumped model (section 1.5), whose application to a large catchment involves a subdivision of the total area into smaller units or subcatchments which are assumed to exhibit similar hydraulic and hydrological characteristics. Solution begins at the upstream portion of the catchment, and proceeds downstream in the manner described in section 1.5 and figure 5. The final outflow hydrograph represents the integrated response of the whole catchment.

HYMO contains a number of hydrological and model control procedures. Conveniently, each of these is contained within the program implementation in a separate subroutine. The structure of the HYMO program (Williams and Hann, 1972 1973) is outlined in figure 7.

Figure 7 The basic structure of HYMO



Hydrological procedures (indicated in the lower row of figure 7) are invoked to generate the outflow hydrograph for a subcatchment area, to perform routing calculations through channels and reservoirs, and to calculate sediment yield. Model control procedures are used to instruct the program to begin, to store a measured hydrograph or rating curve, to add two hydrographs together, to provide hard copies of printed or plotted information, to perform error analyzes on hydrograph predictions, and to finish. The user may select the order in which the procedures are effected. This allows for a good deal of flexibility in application to each particular catchment. An example of the form of the data file which a user must provide is illustrated in figure 8. The data which are required by each procedure is disclosed in table 7.

As modelling begins at the most upstream subcatchment, and proceeds downstream by cumulating hydrographs (figure 5), it is not necessary to store all of the information which is generated. At any one time, the program stores up to six hydrographs and six rating curves in core memory. This makes the model economical in terms of computer storage requirements, an attractive facility for economical and operational use.

The hydrological and model control procedures will now be examined in more detail.

2.1.1 Hydrological procedures

There are four hydrological procedures in HYMO, and these are indicated in the lower row of figure 7. (The compute rating curve, compute travel time, and route hydrograph through channel subroutines combine to form the flood routing hydrological procedure.) Attention in this thesis is drawn in particular to the method of hydrograph computation; however at this point, the details of all hydrological procedures will be presented. It should be noted that all parameter units in this subsection are in imperial units.

Hydrograph computation A standard three stage procedure is used to generate the storm hydrograph for each subcatchment. Firstly, a unit

Command	Required input
START	RAINFALL BEGINS AT 12.5 HRS
STORE HYD	ID=1 HYD NO=301 DT=0.2 HR DA=1.5 SQ MI FLOW RATES (ft^3s^{-1}): 0 10 50 100 500 1000 1800 2000 1900 1500 1200 800 600 500 400 300 200 100 50 10 1
COMPUTE HYD	ID=2 HYD NO=302 DT=0.5 HR DA=2.1 SQ MI CN=90 HT= 100 FT L=3.3 MI CUMULATIVE RAINFALL (ins): 0 .31 .61 1.04 1.85 2.74 3.06 3.45 4.33 3.75
PRINT HYD	ID=2
PLOT	ID=2
STORE RATING CURVE	ID=2 VS NO=15 ELEV AREA FLOW 497 0 0 497 2 1 498 9 19 499 19 52 500 30 98
COMPUTE TRAVEL TIME	ID=2 REACH NO=8 NO VS=15 L=4500 FT SLP=.0075
ROUTE	ID=2 HYD NO=303 INFLOW ID=1 DT=.25 HR
ADD HYD	ID=2 HYD NO=303 ID=2 HYD=302
FINISH	

Figure 8: An example of the form of data file which the user must supply for HYMO

Table 7: Data requirements of HYMO

Hydrological procedures
COMPUTE HYDROGRAPH Storage location number for hydrograph Hydrograph identification number Time increment for rainfall data Watershed area, height, main stream length Curve number Rainfall cumulative totals
COMPUTE RATING CURVE Storage location number for rating curve Cross section reference number Number of segments in section (Normally 3, 2 flood plain and 1 channel, where more than 1 channel, up to 6 permitted) Maximum and minimum elevation Channel and flood plain slope Channel and flood plain manning n Cross section coordinates
COMPUTE TRAVEL TIME Storage location number Reach identification number Number of valley sections in reach Reach length Slope (either channel of flood plain, or weighted average of the two)
ROUTE Storage location number of in and outflow hydrographs Hydrograph identification number of outflow hydrograph Time increment
ROUTE RESERVOIR Storage location number of in and outflow hydrograph Hydrograph identification number, outflow hydrograph Individual points on reservoir outflow-storage relation (limited to 20 points)
SEDIMENT YIELD Storage location number of hydrograph Soil, crop, conservation and gradient factors Slope length

Continued on following page ...

Table 7 ... continued from previous page

Model control procedures
START Start time
STORE HYDROGRAPH Storage location number for hydrograph Hydrograph identification number Time increment for discharge data Watershed area Discharge (Limited to 300 points)
STORE RATING CURVE Storage location number for rating curve Valley section number Rating curve points elevation, end area, flow rate (Limited to 20 points)
ADD TWO HYDROGRAPHS Storage location number for resultant hydrograph Hydrograph identification number of resultant Storage location of two hydrographs to be added
PRINT HYDROGRAPHS Storage location number for hydrograph Code specifying full or abbreviated output
PLOT HYDROGRAPH Storage location number of the 1 or 2 hydrographs to be plotted
ERROR ANALYSIS Storage location numbers of 2 hydrographs to be compared
FINISH No information required

hydrograph is derived synthetically for each subcatchment area from its physical characteristics. Secondly, direct or surface runoff is determined using the United States Department of Agriculture (USDA) Soil Conservation Service (SCS) curve number method (USDA SCS, 1972), and thirdly, these are convolved to produce the flood hydrograph for the subcatchment.

This three stage procedure is entirely empirical (the model has in effect, been precalibrated on a variety of gauged watersheds) and therefore involves extrapolation from the range of conditions for which calibration was achieved. However, in terms of its data and computer resource requirements, the hydrograph computation procedure does satisfy the ungauged and operational requirement.

A dimensionless unit hydrograph method is used by HYMO. This has been synthesized from measured hydrographs from 34 catchments in Texas, Oklahoma, Arkansas, Louisiana, Mississippi, and Tennessee. These catchments range up to 16 square km in area. The synthesized dimensionless unit hydrograph (figure 9A) is described by a two parameter gamma distribution. For the beginning of the discharge rise ($t=0$) to the inflection point (t_0), discharge is given by:

$$u_t = u_p (t/t_p)^{(n-1)} e^{(1-n)(t/t_p-1)} \qquad (7)$$

Where:

u_t - unit hydrograph discharge at time t ($ft^3 s^{-1}$)
u_p - unit hydrograph peak discharge ($ft^3 s^{-1}$)
t_p - time to peak (hours)
n - dimensionless parameter
(a function of k_1/t_p, figure 9B)
k_1 - the first recession constant

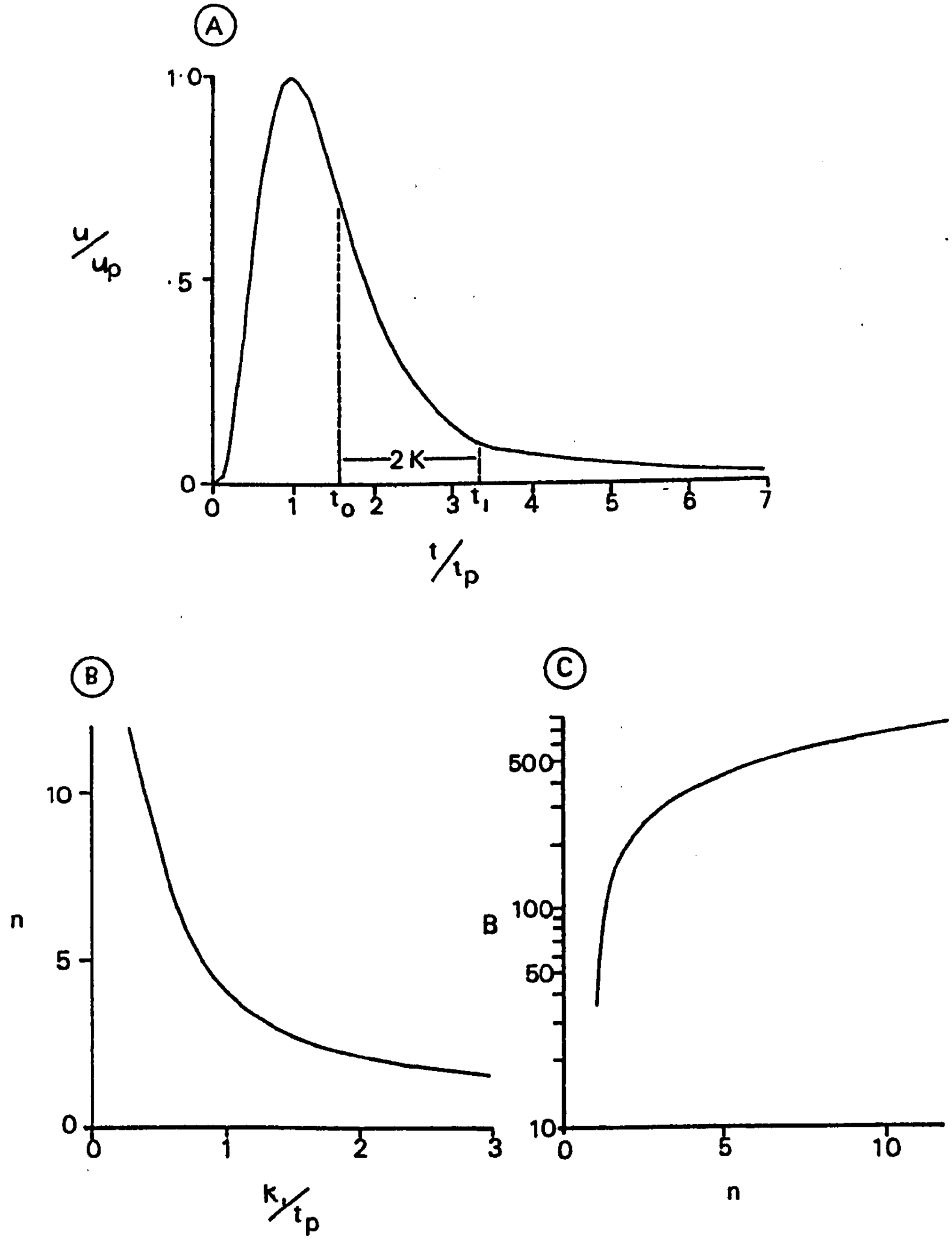


Figure 9: Dimensionless unit hydrograph derivation (after Williams and Hann, 1972, figures 1, 2, and 3) (A) Dimensionless unit hydrograph (B) Relationship between n and k_1/t_p (C) Relationship between B and n

For t_0 to t_1, where:

$$t_1 = t_0 + 2k_1 \tag{8}$$

and:

$$t_0 = 1 + t_p \surd(1/(n-1)) \tag{9}$$

the recession depletion equation becomes:

$$u_t = u_0 e^{((t_0-t)/k_1)} \tag{10}$$

Where:

t_0 - time at inflection point (hours)
u_0 - unit hydrograph discharge at inflection point ($ft^3 s^{-1}$)

$$u_0 = u_p (100(1+\surd(1/(1-n)))^{n-1} e^{(1-n)(100(1+\surd(n-1))-1)} \tag{11}$$

Finally, for t_1 to infinity, the recession depletion equation becomes:

$$u_t = u_1 e^{((t_1-t)/k_2)} \tag{12}$$

Where:

k_2 - the second recession coefficient
$k_2 = 3k_1$
u_1 - unit hydrograph discharge at t_1 ($ft^3 s^{-1}$)

$$u_1 = u_o e^{((t_0-t_1)/k_1)} \tag{13}$$

The actual catchment unit hydrograph associated with a particular storm event can be derived from this dimensionless hydrograph provided that information for the peak discharge (u_p), the time to peak discharge (t_p) and the recession constant (k_1) can be provided. Where, for the ungauged catchment, these data are not available, the following relationships may be used which relate the three characteristics to measurable basin properties such as catchment area, length of main channel, and elevation difference, features which can be derived from a topographic map:

$$u_p = \frac{BAQ}{t_p} \tag{14}$$

Where:

B - dimensionless watershed parameter, a function of n (figure 9C)

A - watershed area (miles^2)

Q - total storm runoff (inches)

$$k_1 = 27.0(A)^{0.231}(SLP)^{-0.777}(L/W)^{0.124} \tag{15}$$

Where:

SLP - total elevation difference (feet) divided by flood plain distance (miles) between catchment outlet and most distant point

L/W - watershed length, width ratio

$$t_p = 4.63(A)^{0.422}(SLP)^{-0.46}(L/W)^{0.133} \tag{16}$$

Catchment incremental runoff is derived from the curve number method which was developed by the USDA SCS (1972). The relationship between total rainfall and total runoff is described by:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad \text{For } P>0.2(S) \qquad (17)$$

Where:

P - total storm rainfall (inches)
S - catchment storage (inches)

$$S = \frac{1000}{CN} - 10 \qquad (18)$$

CN - runoff curve number

The curve number is a dimensionless coefficient which reflects the hydrological soil type, land use cover, agricultural treatment, and antecedent soil moisture conditions at a catchment scale.

To derive incremental runoff it is necessary to provide information about cumulative precipitation totals at equal time intervals, throughout the storm. The cumulative total runoff associated with each precipitation total is evaluated from application of equation (17). Incremental runoff for each time interval is then derived by subtracting each cumulative runoff total at time (t) from that at time (t+1).

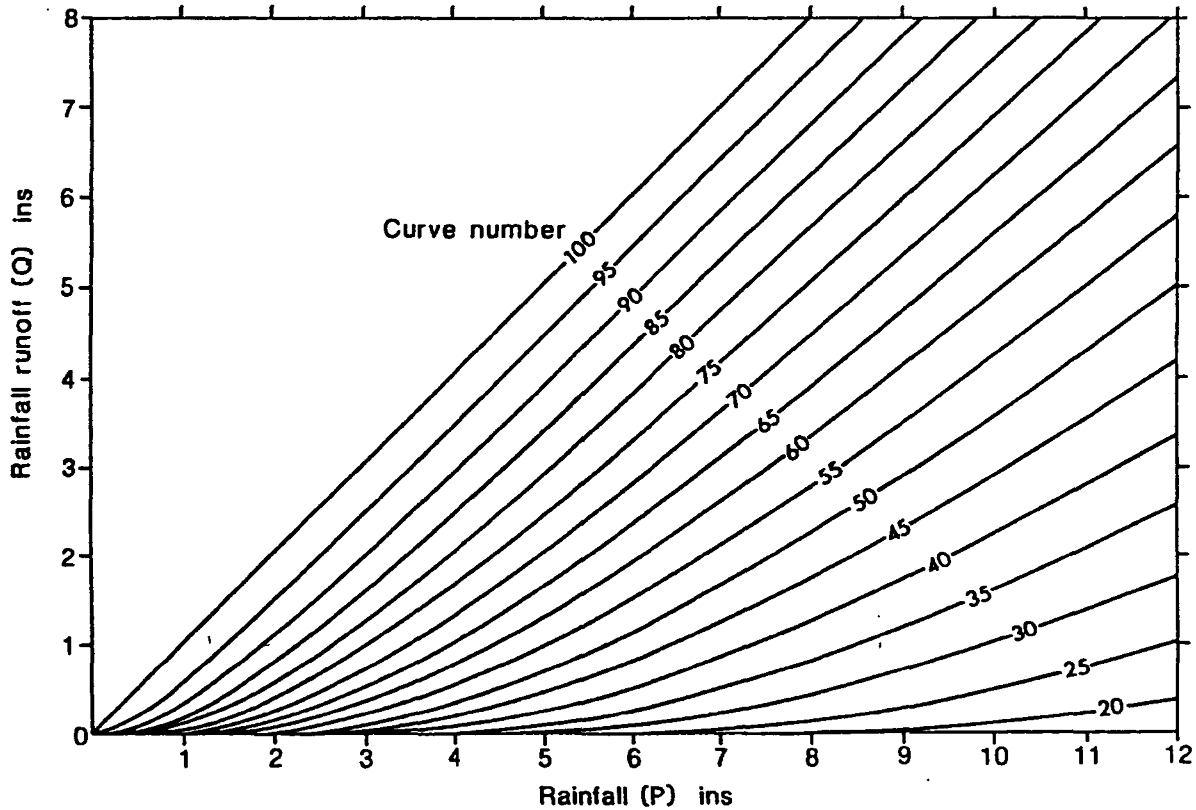
The curve number model allows for an initial abstraction of 20%, which represents the net effect of interception, infiltration, and surface storage. To define runoff therefore, there are two data requirements for each subcatchment: the precipitation and a representative curve number value.

Figure 10 provides a graphical solution of equation 17. Curve number values approaching 100 are seen to represent high runoff conditions from cultivated land, and lower values represent the reduced runoff from well vegetated areas.

There are two methods of estimating the value of the watershed curve number. For the ungauged catchment, data concerning the hydrological soil group, agricultural practices, and hydrological condition can be derived from soil survey maps. This information, together with the USDA tables (table 8) may be used to estimate the curve number. The SCS define 4 hydrological soil groups:

A (Low runoff potential) Soils with high infiltration rates even when thoroughly wet.
B Soils with moderate infiltration rates when thoroughly wet.
C Soils with slow infiltration rates when thoroughly wet.
D (High runoff potential) Soils with very slow infiltration rates when thoroughly wet.

Where variability of soil hydrological group, agricultural practices, and hydrological condition cannot be ignored, a single integrated watershed curve number is determined by weighting each curve number according to the percentage area in which it occurs and then summing all values. The curve number thus derived represents an average antecedent moisture condition (AMC II) for the catchment. For application of this method to any particular storm event, this curve number may be further adjusted according to the soil antecedent moisture conditions. Depending on the previous five day rainfall totals, and whether the storm occurs in the dormant or in the growing season (table 9) the curve number can be adjusted to either a drier (AMC I), or wetter (AMC III) condition (table 10).



Curves are valid for the case where I_a=0.2S

Figure 10 Graphical solution of the SCS curve number runoff equation (after USDA SCS, 1972, figure 10.1)

Table 8: Runoff curve numbers for hydrological soil-cover complexes (antecedent moisture condition II, inital abstraction 20%) (after USDA SCS, 1972, table 9.1)

Cover			Hydrological soil group			
Land use	Treatment or practice	Hydrological condition	A	B	C	D
Fallow	Straight row	---	77	86	91	94
Row crops	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Contoured & terraced	Poor	66	74	80	82
	Contoured & terraced	Good	62	71	78	71
Small grain	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Contoured & terraced	Poor	61	72	79	82
	Contoured & terraced	Good	59	70	78	81
Close-seeded legumes * or rotation meadow	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
	Contoured & terraced	Good	51	67	76	80
Pasture or range		Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
Farmsteads		---	59	74	82	86
Roads	Dirt	---	72	82	87	89
	Hard surfaces	---	74	84	90	92

* Close drilled or broadcast

Table 9: Seasonal rainfall limits for antecedent moisture conditions (adapted from UDSA SCS, 1972, table 4.2)

AMC group	Total 5-day antecendent rainfall (mm)	
	Dormant season	Growing season
I	< 12.70	< 35.56
II	12.71 - 27.94	35.57 - 53.34
III	> 27.95	> 53.35

Table 10: Curve numbers for drier (AMC I) and wetter (AMC III) antecedent soil moisture conditions (adapted from USDA SCS, 1972, table 10.1)

CN for AMC II	CN for conditions I	CN for conditions III
100	100	100
99	97	100
98	94	99
97	91	99
96	89	99
95	87	98
94	85	98
93	83	98
92	81	97
91	80	97
90	78	96
89	76	96
88	75	95
87	73	95
86	72	94
85	70	94
84	68	93
83	67	93
82	66	92
81	64	92
80	63	91
79	62	91
78	60	90
77	59	89
76	58	89
75	57	88
74	55	88
73	54	87
72	53	86
71	52	86
70	51	85
69	50	84
68	48	84
67	47	83
66	46	82
65	45	82
64	44	81
63	43	80
62	42	79
61	41	78
60	40	78
59	39	77
58	38	76
57	37	75
36	36	75
55	35	74
54	34	73
53	33	72
52	32	71
51	31	70
50	31	70
49	30	69
48	29	68
47	28	67
46	27	66
45	26	65
44	25	64
43	25	63
42	24	62
41	23	61
40	22	60
39	21	59
38	21	58
37	20	57
36	19	56
35	18	55
34	18	54
33	17	53
32	16	52
31	16	51
30	15	50
25	12	43
20	9	37
15	6	30
10	4	22
5	2	13
0	0	0

For the gauged catchment, where rainfall and the corresponding runoff data are available, an optimum curve number can be calculated according to the following equation established by Hawkins (1979):

$$CN = \frac{100}{1+0.5(P+2Q-\sqrt{(4Q^2+5PQ)})} \tag{19}$$

Finally, the direct runoff is convolved with the unit hydrograph to produce the flood hydrograph describing the outflow of the subcatchment, according to the following equation:

$$q_t = \sum_{i=1}^{n} \sum_{j=1}^{i} (u_{(j)} r_{(i-j+1)}) \tag{20}$$

Where:

n - number of time intervals of hydrograph
q_t - flood hydrograph discharge at time t ($ft^3 s^{-1}$)
r_t - runoff at time t (inches)

Channel Flood Routing To perform channel flood routing, the user invokes the compute rating curve, compute travel time, and route hydrograph through channel subroutines. Flood routing through a channel is performed in order to determine the rate of movement and changes in form of the flood wave as it passes downstream. Typically, the time of the peak discharge will be later downstream, and the peak flow will be reduced. The downstream movement of a flood wave is a highly complex series of changes, as channel flow is nonsteady and nonuniform. Variation in channel properties and lateral inflow also introduce complications.

A revised version of the Variable Storage Coefficient method has been incorporated into HYMO. This represents a compromise between very simple storage models and those methods based on the principles of hydraulics. The former are based upon continuity (conservation of mass) and a relationship between discharge and storage. They assume a constant travel time and storage coefficient. They have conservative data requirements and require only very simple calculations; they consequently make many very simplifying assumptions. The latter are based upon the hydrodynamic equations of continuity and momentum, the Saint Venant equations, which describe the nature and behaviour of gradually varying, unsteady flow in open channels. Numerical methods are normally required to solve these nonlinear partial differential equations. However, under certain conditions, the kinematic wave approximation may be valid. This assumes that inertial forces are negligible relative to gravitational and frictional forces and that flow is a function of depth alone. The momentum equation is replaced by a relationship between stage and discharge, based on either the Chezy or the Manning friction factor. This approximation allows for an analytical solution, thus reducing the cost and complexity of obtaining a solution. However both the Saint Venant equations and the kinematic approximation are demanding in terms of data, computer resources, and experience of the user. In addition, it is not always possible to provide estimates for all parameters without resort to calibration.

Williams (1969) presents the Variable Storage Coefficient method, and provides a solution for it. In comparison to basic storage routing models, this method is considered to be a better approximation to reality as it does allow the storage coefficient and travel time to vary with river stage. It is considered to be reliable for a range of river flow conditions and reach lengths, and may be applied to routing of both channel and flood plain flows.

Application of this method requires a relationship between stage, end area, and discharge to be defined for the particular reach. If a measured relationship is not available, it can be derived by application of the Mannings equation, which is simple, easy to use, and not too demanding in terms of data. Discharge (q) is given by the following equation:

$$q = \frac{1.486}{'n'} (aR^{2/3} Sl^{1/2}) \tag{21}$$

Where:

'n' - Mannings coefficient of roughness
a - cross section area (ft^2)
R - hydraulic radius (ft)
Sl - slope of energy gradient

Twenty values on the rating curve are established by HYMO.

Given the inflow hydrograph for a reach with disharge values at equal time intervals, the outflow hydrograph can be calculated from the following equations. As a variable storage coefficient and travel time are assumed, these equations are recalculated for each discharge:

$$O_{t+\Delta t} = C_{t+\Delta t} [\bar{I}+((1/C_t) -1)O_t] \tag{22}$$

$$C_{t+\Delta t} = \frac{2 \Delta t}{2T_{t+\Delta t} + \Delta t} \tag{23}$$

$$C_t = \frac{2 \Delta t}{2T_t + \Delta t} \tag{24}$$

$$T_t = \left(\frac{L}{1800(Vi_t + Vo_t)}\right)\left(\frac{(L)(SLP_0)}{(L)(SLP_0) + Di_t - Do_t}\right)^{1/2} \qquad (25)$$

$$T_{t+\Delta t} = \left(\frac{L}{1800(Vi_{t+\Delta t} + Vo_{t+\Delta t})}\right)\left(\frac{(L)(SLP_0)}{(L)(SLP_0) + Di_{t+\Delta t} - Do_{t+\Delta t}}\right)^{1/2} \qquad (26)$$

Where:

- I_t - inflow discharge at time t ($ft^3 s^{-1}$)
- O - outflow discharge at time t ($ft^3 s^{-1}$)
- $\bar{I}$ - average inflow discharge during time interval t ($ft^3 s^{-1}$)

  $$\bar{I} = \frac{I_t + I_{t+\Delta t}}{2}$$
- C - storage coefficient for particular discharge
- T - travel time for particular discharge (hrs)
- L - reach length (ft)
- Vi - velocity of inflow at time t (discharge divided by end area) ($ft\ s^{-1}$)
- Vo - velocity of outflow at time t ($ft\ s^{-1}$)
- SLP_0 - normal slope
- Di - depth of inflow at time t (ft)
- Do - depth of outflow at time t (ft)
- Δt - time interval, constant throughout (hrs)

The solution for these equations is iterative, but no convergence problems have been experienced.

Reservoir Routing The Storage Indication method is used to route hydrographs through reservoirs (USDA SCS, 1972). This uses the relation:

$$O_{t+\Delta t}=2(I_t+(S_t/\Delta t)-(S_{t+\Delta t}/\Delta t))-O_t \qquad (27)$$

This method requires that a storage discharge relationship be specified for the reservoir.

Sediment Yield The Universal Soil Loss equation, modified to allow sediment yield to be calculated for the individual storm, was incorporated into HYMO. This relation is given by:

$$Sy = 95.0[(q_p)(R)]^{0.56}(E)(Cr)(Pr)(LS) \qquad (28)$$

Where:

Sy - sediment yield (tons)
q_p - peak discharge ($ft^3 s^{-1}$)
R - runoff volume (acre ft)
E - soil erodibility factor
Cr - cropping management factor
Pr - erosion control practice factor
LS - slope length and gradient factor

2.1.2 Model control procedures

A number of model control procedures are also included in HYMO. These are illustrated in the upper row of figure 7. The user may select model control procedures in any order, or combination, to instruct the program to begin, to store a measured hydrograph or rating curve, to add two hydrographs together, to provide printed or plotted information, to analyze results and to terminate. A short description of each will serve to illustrate the flexibility which HYMO offers the user.

Start This provides the program with the start time for the simulation and instructs the program to begin.

Store hydrograph This allows the user to input a measured hydrograph for a particular subcatchment, directly into the computer memory. All hydrographs are limited to 300 points.

Store rating curve This allows a measured rating curve for a particular cross section to be input directly into the computer memory. A maximum of twenty points to define the stage, end area, discharge relationship are permitted.

Add two hydrographs Figure 5 has illustrated that as a semi-lumped model, HYMO initially calculates the hydrograph for the upstream subcatchment area and proceeds downstream by cumulating pairs of hydrographs. This model control procedure adds together the coordinates of two specified hydrographs.

Print hydrograph According to the user's request, this procedure will either print out the whole of the hydrograph, or just the runoff volume and peak discharge rate values to a user specified peripheral.

Plot hydrograph This enables one or two hydrographs to be plotted out on the same axis. The plot is made on a line printer.

Error analysis This model control procedure offers two quantitative measures of the goodness of fit of two hydrographs. The first measure, the error standard deviation (ESD), compares the two hydrographs overall, and is given by:

$$(ESD)^2 = \frac{\sum_{i=1}^{n} (qm_i - qc_i)^2}{n} \tag{29}$$

Where:

- n - number of pairs of discharge measurements at equal time intervals
- qm_i - measured discharge ($ft^3 s^{-1}$)
- qc_i - calculated discharge ($ft^3 s^{-1}$)

This statistic is evaluated over the duration of the shorter hydrograph. A smaller value of the error standard deviation indicates a closer fit of the estimated to the measured hydrograph. The second measure, the percentage peak discharge error (PDE), quantifies the percentage difference between the two peak discharges:

$$PDE = \frac{q_p m - q_p c}{q_p m} \times 100\% \tag{30}$$

Where:

- $q_p m$ - measured peak discharge ($ft^3 s^{-1}$)
- $q_p c$ - calculated peak discharge ($ft^3 s^{-1}$)

<u>Finish</u> When all hydrological and model control procedures which are required by the user have been completed, this procedure instructs the program to terminate.

2.2 Identification of areas for improvement of HYMO

Smith (1976) applied HYMO to the Mud Spring Hollow, a catchment in Wyoming. This has an area of 22.875 square km, and comprises mainly clay. Figure 11 provides the measured and simulated peak discharge for a range of seven storms. For six of the seven, HYMO underpredicts the peak discharge, and overall the fit of the predicted to the measured is not good. Smith (1976) attributed this to an inadequate representation of the areal variation of precipitation. However, there is evidence to suggest that HYMO is more sensitive to error in the curve number than to error in precipitation. Indeed Smith (1976) presented the results of a sensitivity analysis of HYMO, and these are summarized in figure 12. Peak discharge is demonstrated firstly to be most sensitive to the curve number selected, and secondly to precipitation. Change in the catchment characteristics, length, area, and height produce almost proportional change in peak discharge.

Hawkins (1975) provided further evidence for the sensitivity of runoff values predicted by equation (17) to the curve number. The results which he provided are given in figure 13. This figure indicates the absolute percentage error in the calculation of runoff, assuming a 10% error in either rainfall or curve number inputs, and demonstrates that over a considerable range of rainfall totals (up to nine inches of precipitation), error in the estimation of curve numbers has far more serious consequences than error of a similar magnitude in precipitation. Errors are particularly marked near the threshold of runoff (low runoff and low rainfall conditions). Clearly, an accurate estimate of the ungauged catchment curve number is critical for discharge predictions.

Bales and Betson (1982) have also drawn attention to the regularity with which, over a total of 585 storms and 36 catchments, the use of ungauged estimates of curve number (AMC II) underestimates runoff volumes. These curve numbers were substantially lower than the optimum, calculated values. Only 5% of AMC II and 15% of AMC III predictions were within 20% of the observed runoff. Wood and Blackburn (1984) evaluated the

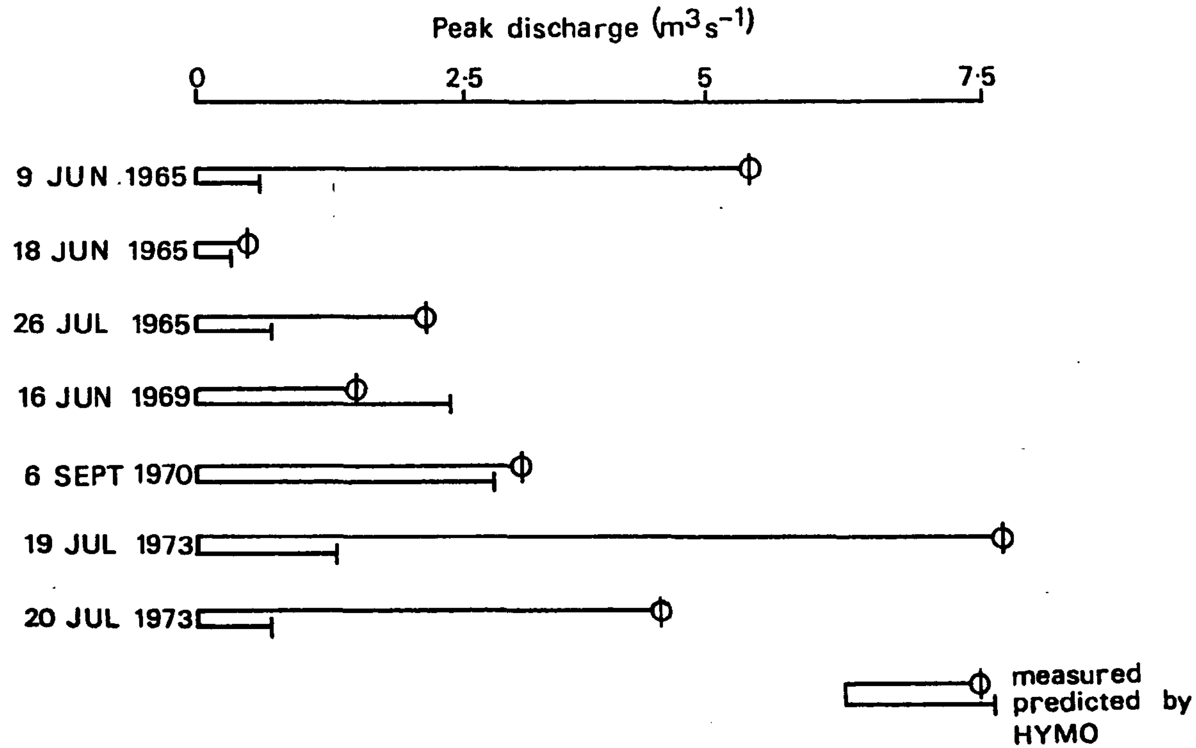


Figure 11 A comparison of measured peak discharge to that provided by HYMO, for the Mud Spring Hollow, Wyoming (adapted from Smith, 1976, table 1)

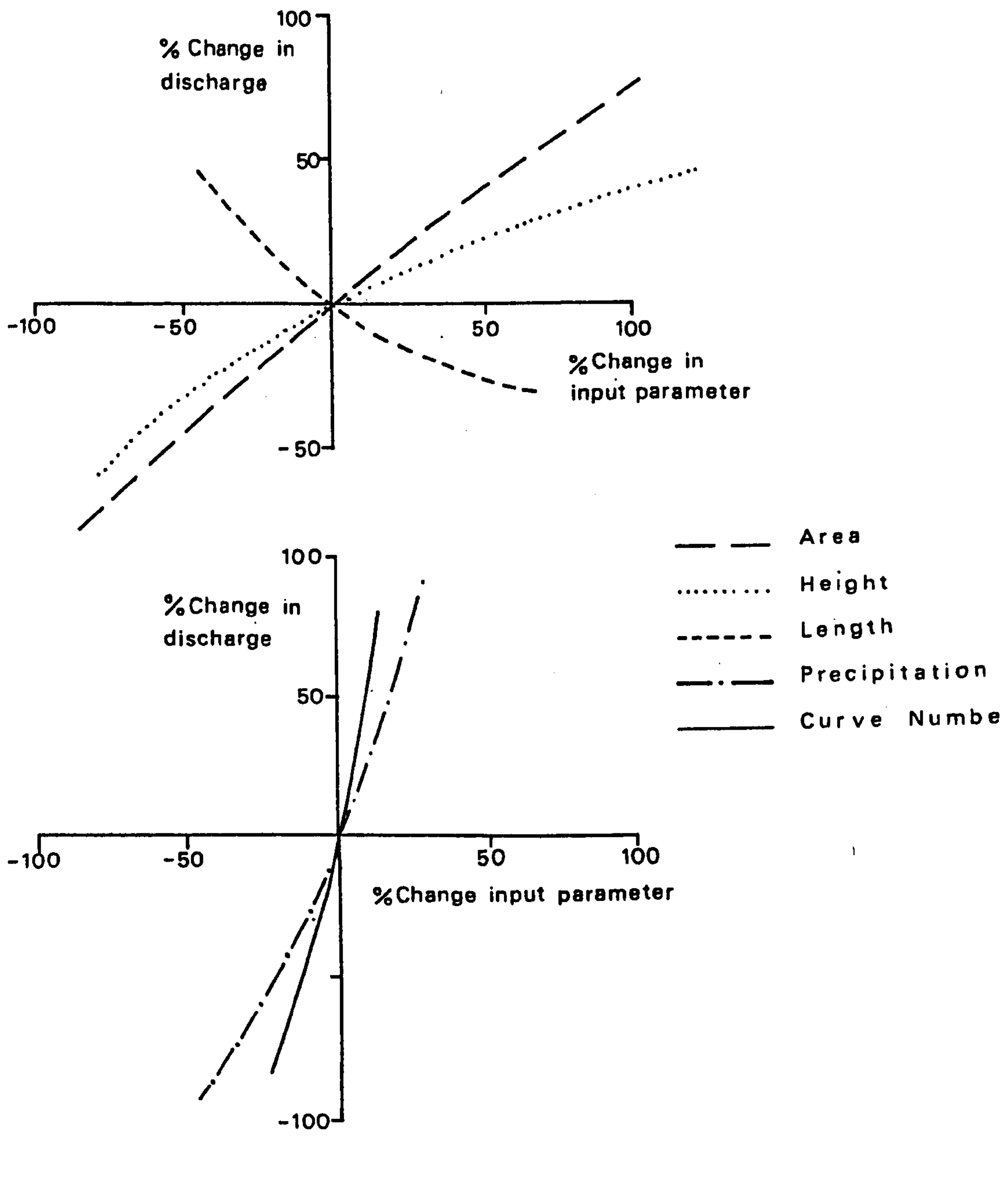


Figure 12: Results of a sensitivity analysis of HYMO (adapted from Smith, 1976, figures 12, 13, and 14)

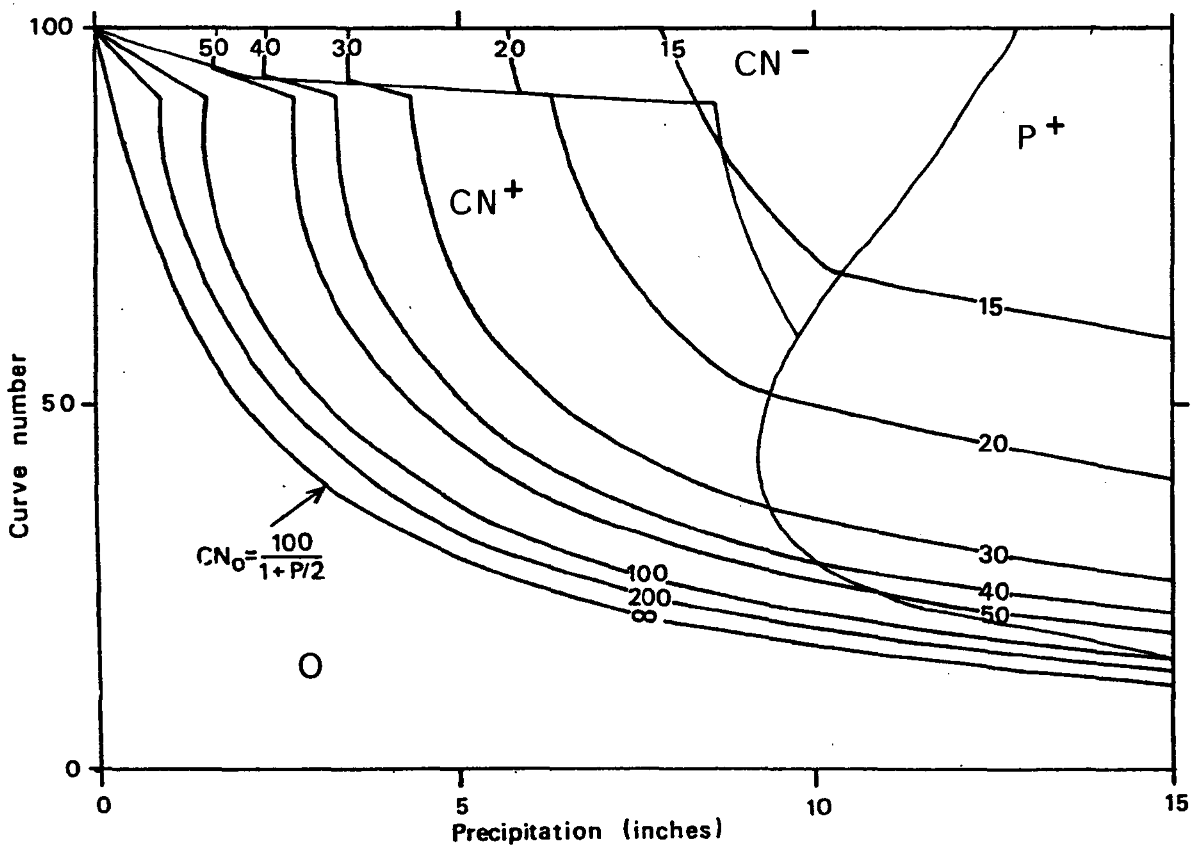


Figure 13 The absolute error (%) in the calculation of runoff from the curve number method, assuming 10% error in rainfall or curve number inputs (adapted from Hawkins, 1975, figure 2)

curve number method in semi-arid and arid rangelands and found runoff to be overestimated for 67% of applications, and correctly estimated for only 11% of applications.

As a procedure to determine the volume of direct runoff caused by a given amount of rain, the curve number method does have certain attractions:

1 It is simple to understand and easy to use.
2 It is computationally efficient and can be applied rapidly.
3 It has conservative data requirements.
4 It incorporates the effects of soil type, land use and management practices.
5 It has been used for many years, and so the method is well established and accepted.
6 It provides a coefficient describing runoff potential at a catchment scale.
7 It has good documentation which is due in part to its Government agency origin.
8 There is a lack of a suitable alternative.

However, it is proposed here that use of the curve number method may account for the inaccurate estimates of runoff volume and hence of peak discharge. As Hawkins (1979, p375) suggested, although the curve number procedure "..has appeal to practitioners, it is usually of little interest to most scientific hydrologists".

Prior to developing a detailed criticism of the curve number procedure, its evolution deserves closer attention. It should be noted that all parameters units in this subsection are in imperial units.

2.2.1 Basis of curve number procedure

The curve number procedure for generating catchment runoff is based upon the assumption that for a single storm, where initial abstraction of rainfall does not occur, rainfall, runoff, and storage (rainfall not converted into runoff) are related in the following manner:

$$\frac{P-Q}{S'} = \frac{Q}{P} \tag{31}$$

Where:

S' - potential maximum storage (inches)

Solving for Q, a relationship between rainfall and runoff (where inital abstraction can be ignored) may be derived:

$$Q = \frac{P^2}{P+S'} \tag{32}$$

Initial abstraction of precipitation by the processes of interception, infiltration, and surface storage does occur and its omission represents a gross over simplification. It is introduced into the relationship by modification of the terms P and S'. Equation (31) can thus be rewritten:

$$\frac{(P-I_a)-Q}{S} = \frac{Q}{P-I_a} \tag{33}$$

Where:

I_a - inital abstraction (inches)

S - $S'+I_a$

Solving again for Q:

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \tag{34}$$

An empirical relationship between I_a and S was derived by the SCS from data from many small catchments (figure 14). It is of the nature:

$$I_a = 0.2(S) \tag{35}$$

Equation (35) is substituted into equation (34) to derive the relationship between rainfall and runoff, given in equation (17).

2.2.2 Critique of the curve number procedure

A number of criticisms of the curve number method can be made.

1 Runoff predictions are highly sensitive to the curve number. This has been illustrated in the beginning of this section with examples from Hawkins (1975), Bales and Betson (1982), and Wood and Blackburn (1984). However, despite the importance of an accurate determination of curve number for the ungauged catchment, parameter estimation relies upon a semi-objective procedure which is demanding on the user as it relies solely upon "...major professional judgement" (Hawkins, 1980, p925).

2 The curve number is dependent not only on catchment and antecedent conditions, but also on storm characteristics. Determination of a catchment curve number which is independent of storm size or intensity is not appropriate for all conditions (Hawkins, 1978a, 1979; Simanton et al, 1973).

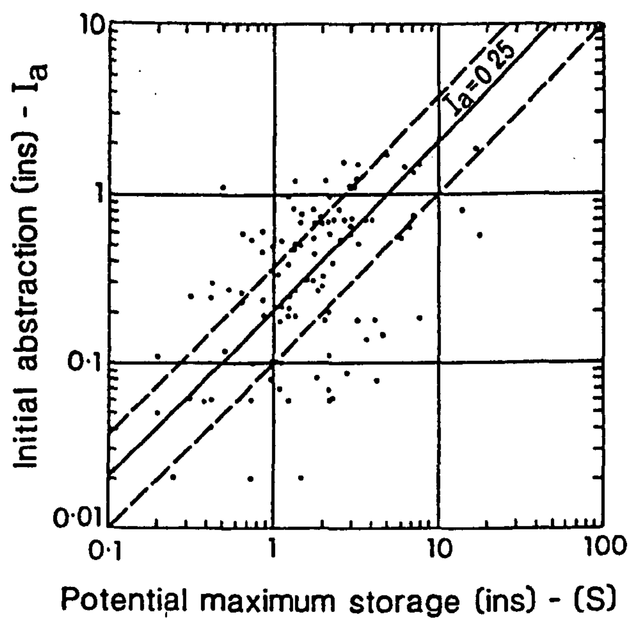


Figure 14: The relationship of initial abstraction (I_a) and storage (S) (after USDA SCS, 1972, figure 10.2)

3 Certain theoretical problems with the curve number method have been identified. Morel-Seytoux and Verdin (1981) have questioned the theoretical basis of the model. They argued that although equation (31) can be justified for long duration storms which experience no initial abstraction, it was their opinion that there is no physical reason for assuming that these ratios will be equal under any other conditions.

4 Morel-Seytoux and Verdin (1981) and Hjelmfelt (1980) have demonstrated the infiltration behaviour implied by the model to be in direct physical disaggreement with physical infiltration theory, and especially when applied to individual storms which are not of uniform intensity. Under these conditions, discontinuous infiltration rates occur, and misleading runoff predictions are therefore made. Morel-Seytoux and Verdin (1981) derived the following equation:

$$i = \frac{S^2 r}{(P - I_a + S)^2} \tag{36}$$

Where:

i - infiltration rate (ins hr^{-1})
r - rainfall rate (ins hr^{-1})

Here, r appears in the numerator which implies, quite incorrectly, that the infiltration rate varies in direct proportion to rainfall intensity. HYMO divides total precipitation into equal time periods, applying equation (17) to each in turn. As demonstrated by Morel-Seytoux and Verdin (1981), for rainfall of varying intensities, the method estimates highly discontinuous and unrealistic infiltration rates. This situation has been illustrated by Anderson and Howes (1984) for a catchment in Arkansas where CN=85. Figure 15 shows the nature of the infiltration rate for the storm indicated.

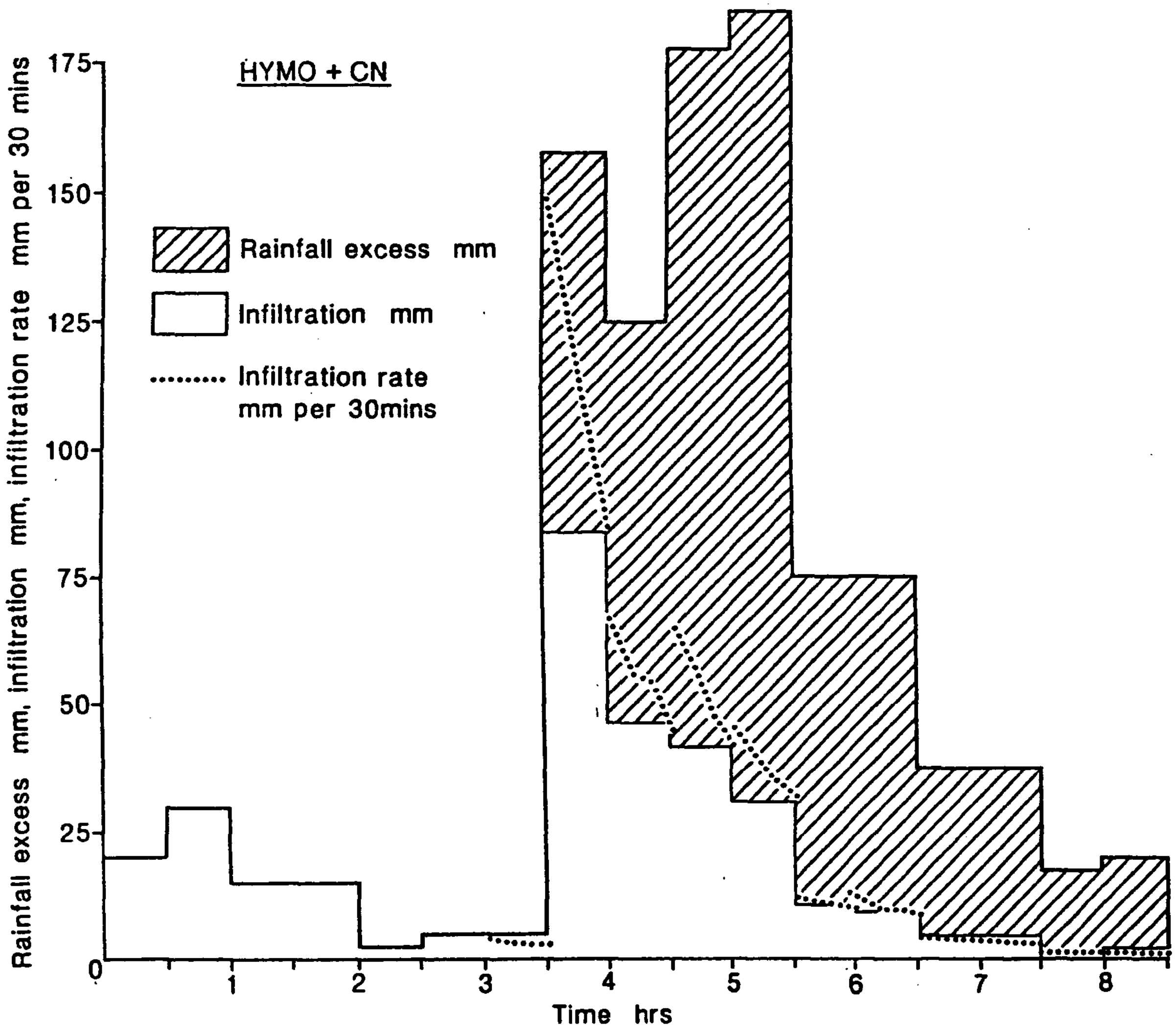


Figure 15 The nature of the infiltration rate predicted by the SCS curve number method

Morel-Seytoux and Verdin (1981) proceeded to show that the excess rainfall predicted by the method is also unrealistic. They derived the following equation for rainfall excess (r_e):

$$r_e = \frac{(P-I_a)(P+2S-I_a)r}{(P-I_a+S)^2} \qquad (37)$$

and suggested that once surface ponding occurs, rainfall excess will be predicted provided that there is some rainfall, but regardless of the relationship of rainfall intensity and infiltration capacity. Infiltration rates do not approach an equilibrium infiltration capacity. This leads to runoff predictions during low rainfall intensities near the end of storms.

5 Antecedent soil moisture conditions have a significant influence on runoff, and the curve number method can be criticized for the inadequate and very simple method by which these are incorporated into the model. Two major weaknesses of this procedure may be identified. Firstly, antecedent moisture content is portrayed as existing in discrete classes. In reality, it will vary continuously with soil moisture. Very large differences in calculated stormflows can be derived depending on the antecedent moisture condition class which has been chosen (Hawkins, 1978b; Williams and LaSeur, 1976; Hope and Schulze, 1982). Secondly, the use of the previous five day rainfall (table 9) as a criteria for the choice of the antecedent soil moisture conditions is not physically based, but a subjective assessment. The use of just the two seasons, dormant and growing, does not adequately take into consideration the depletion of catchment storages due to evaporation and drainage. This will also vary with region.

As Hjelfelt et al (1982) and Cronshey (1983) have pointed out, antecedent soil moisture cannot be invoked to explain the total variation in curve numbers. They stress also the effects of plant growth, temperature, evaporation, soil crusting, and rainfall intensity. These all interact with antecendent soil moisture to affect the timing and amount of runoff associated with a storm event.

6 The use of four soil hydrological soil groups has been criticized by Rallison (1980) who has suggested that a more detailed subdivision of groups would be more appropriate. Indeed, Wood and Blackburn (1984) found that for semi-arid and arid rangelands, hydrological soil groups provide a very poor basis for estimating infiltration rates, and suggest that a classification based upon soil surface characteristics would be more suitable.

7 There are two problems with assuming a constant initial abstraction of 20%. Firstly, this is not physically based; initial abstraction cannot be assumed to be constant. It will depend on storm characteristics, being much smaller for intense storms in comparison to gradual rains. Secondly, as Morel-Seytoux and Verdin (1981) stressed, the scatter around the relationship between I_a and S in figure 14 is very great, especially taking into consideration that the points are plotted on a log-log plot.

8 The curve numbers are location dependent. Different parts of the country display different runoff potential for similar land covers (Rawls et al, 1981). Although USDA SCS (1972) provided supplementary tables for curve numbers for selected covers, for example for coffee and sugar cane in Puerto Rico, for California, for Hawaii and for rangeland, Springer et al (1980) stressed the importance of calculating curve numbers by local optimization to guide the sensible use of tables. Significant deviations from table values have been derived for example for rangelands and for sugar cane and pineapple fields in Hawaii (Cooley and Lane, 1980).

It is essential that a balanced view should be given of the status of the curve number method, and having drawn together a number of criticisms which have been made of its use, it is only fair that attention should be drawn to the following point. Rallison (1980), Rallison and Miller (1982), Bales and Betson (1982), and Chen (1982) have all stressed that many of these critisms are not valid, as the method has been applied well beyond the range for which it was originally intended and developed.

The curve number model was established, and is most effective, as an "...index of runoff potential over a 24 hour period" (Rallison, 1980, p921). It was not designed to recreate the infiltration behaviour for any one specific storm, and consequently is not suitable for establishing incremental runoff for an individual storm, the capacity in which it is used in HYMO. It is also not suitable where there is a major proportion of subsurface flow in catchment runoff, where only a portion of the catchment is contributing to runoff, or where rainfall intensity displays significant variation over the catchment.

The model has been criticized for not including time as an independent variable, because, as a consequence, it cannot distinguish storms of different intensity. It was, however, originally designed for the situation in which only daily rainfall totals were likely to be available, and any more precipitation detail would have been an unreasonable requirement. As Rallison (1980) pointed out, the curve number method is not a state of the art infiltration model, and alternative relationships are available.

To complete this assessment of the curve number method, it should be stressed that the method has been significantly improved. More realistic methods of incorporating antecendent soil moisture conditions have been implemented by Simanton at al (1973), Williams and LaSeur (1976), Hawkins (1978b), and Gray et al (1982).

The above review indicates that the use of the curve number method in HYMO to determine catchment runoff is clearly inappropriate, and that alternative methods for determining catchment runoff for an operational and ungauged application must be examined.

2.3 Review of alternative infiltration models

Infiltration is one of the most important processes in catchment hydrology; it determines, for a given storm, the distribution of rainfall excess available for surface storage and runoff. Its importance in this context has been emphasized by Skaggs and Khaleel (1972), Swartzendruber and Hillel (1973), Hillel (1980), Chong and Green (1980), Slack and Larson (1981), and Woolhiser (1982).

It is useful to review briefly the options available which may be used to model this process. The models may be envisaged as belonging to two groups, exact and approximate models, which are illustrated in table 11. Exact models have been developed mainly by soil physicists for application at a small scale and approximate models have been developed mainly by hydrologists concerned with the application of infiltration models at a catchment scale. Each of these two groups will now be considered.

2.3.1 Exact infiltration models

Soil physicists have applied the laws of unsaturated flow in porous media to soil water flow. Analytical solutions for the nonlinear, partial differential equations which describe flow are only available for very limiting and simple initial and boundary conditions. To enable such models to be applied to complex, more realistic catchment situations, there has been a tendency to develop very sophisticated theories, and numerical solutions for complicated boundary conditions. Theories and numerical solutions are thus available for most aspects of the infiltration process. The complicating factors of layered soils, nonuniform initial moisture conditions, surface sealing and crusting, hystersis, two phase flow, instability of wetting front, nonisothermal systems, infiltration into deforming media, flow through macropores, and variable precipitation intensity may all be taken into account in these physically based models. This has made the solutions more realistic. Interestingly enough, infiltration on a sloping surface, although

Table 11: Classification of infiltration models

EXACT INFILTRATION MODELS:	Application of the laws governing unsaturated flow in porous media
Richards (1931)	
APPROXIMATE INFILTRATION MODELS:	Application of simpler, easier to use equations describing infiltration rate in terms of time, empirical constants, and certain soil parameters.
Empirically derived models	
Kostiakov (1932)	
Horton (1939, 1940)	
Holtan (1961)	
Physically derived models	
Green and Ampt (1911)	
Philip (1957)	
Talsma & Parlange (1972)	
Smith (1972)	

central to hydrological situations, has not received very much attention. Theory does exist therefore, to permit a very good understanding of most aspects of the infiltration process.

Problems do exist however with the application of these infiltration equations at a catchment scale. This is caused by the variability of the prototype system (Philip, 1969, 1975; Bruce and Whisler, 1973; Swartzendruber and Hillel, 1973; Flemming and Smiles, 1975; Raats, 1983; Youngs, 1983). Indeed, Philip (1975, p94) commented:

> "The beautiful economy of analytical scientific methods is soon lost in the sheer magnitude, complexity, and imprecision of the task of synthesis."

In the context of an ungauged and operational hydrological model requirement, the application of some of the more realistic, but complex solutions is precluded due to their very detailed data, and extensive computer resource requirements. However, the utility of some of the more basic physically based infiltration models, such as the one dimensional Richards equation can be considered seriously. Subsection 1.2.1 has drawn attention to a selection of soil data bases and empirical methods which are currently available and which allow for an adequate definition of the soil hydrological properties necessary for application of these models, but which require only very basic soil textural information.

2.3.2 Approximate models

Approximate models have been developed mainly by hydrologists, and comprise simple algebraic equations which express infiltration rates as functions of time, empirical constants and soil parameters. Two types of models are included in this category, and they have very different origins. Firstly, there are empirically derived equations which have been developed from observation. The Kostiakov (1932) equation contains parameters with no physical interpretation, but which are derived from experimental data. Horton (1940) produced an equation which describes the infiltration behaviour which he observed on a runoff plot. Holtan (1961) has provided another empirically derived equation. Alternatively some equations have been derived from application of exact models, but with simplifing assumptions. These have been simplified to enable their application to catchment situations, rather than for predicting infiltration behaviour for a single soil column. Green and Ampt (1911) derived the mathematical solution to soil water flow equations for ponded conditions, into deep homogeneous soils with uniform soil moisture conditions. Water was assumed to enter the soil as a ´slug flow´, resulting in a sharply defined wetting front. Mein and Larson (1971) have extended this approach to compute the quantity of infiltration prior to ponding, and Morel-Seytoux (1978) has extended the method further to account for variable rainfall intensities and for viscous flow of air in the soil. Philip (1957a, 1957b) used the first two terms of the series solution for infiltration from a ponded surface into a deep homogeneous soil. Talsma and Parlange (1972) derived their simplified equation for immediate ponding conditions on the surface, and Smith (1972) derived an equation from the numerical simulation of the Richards equation.

These approximate models do have attractively conservative data and computer requirements, and in this sense are more suitable for application at a catchment scale. Indeed, there are two studies which have examined the replacement of the curve number method with approximate models based on physically based equations. Morel-Seytoux and Verdin (1981) have suggested that infiltration for an individual rainfall, runoff event can be more realistically described by equations based on the Mein and Larson (1971) and Morel-Seytoux (1978) adaptations of the Green-Ampt equations. This method however requires the values of saturated hydraulic conductivity, saturated soil moisture content, and the wetting front suction to be specified for the catchment. The authors provided a methodology for determining these parameters. They related the wetting front suction to the saturated moisture content by a storage suction factor. Curve numbers have been related to particular pairs of soil storage factors and to saturated hydraulic conductivity. This enables an improved infiltration model to be applied, but with no additional data requirements. Brakensiek and Rawls (1983) also applied the Green and Ampt infiltration equations in preference to the curve number method. They presented a summary table which indicates the advantages of a physically based approximate model to the curve number method. This is reproduced in table 12. The physically based infiltration model allows time to be incorporated as an independent variable; the distribution and intensity of precipitation can therefore be included in the model. More accurate measures of the soil hydrologic properties, antecedent moisture conditions, and ground water can be included. A constant initial abstraction does not have to be assumed, but is calculated depending on infiltration, surface conditions and vegetation. Again, the major problem in the use of an infiltration model is in the specification of the Green and Ampt infiltration parameters. The authors offered a series of charts and regression equations which relate all of the necessary parameters to the more easily defined percentage clay, percentage sand, and percentage organic matter. They stressed that extensive soil information is now readily available, at least in the United States, and that this is increasing the feasibility of the infiltration approach to routine runoff prediction.

This research programme aims to investigate the replacement of the curve number method in HYMO with an exact infiltration model. The development and implementation of this infiltration model will be presented in the following section.

Table 12: Comparison of direct runoff prediction approaches (after Rawls et al, 1983, table 1)

Factors	Approach: Curve number	Approach: Infiltration
Precipitation	Rainfall amount	Rainfall intensities or rainfall distribution and amount
Soil	Antecedent moisture condition	Antecedent soil water storage (volume) by soil layers or soil depth
	Hydrological soil group	Soil water properties by layers of soil depth bulk density, saturated conductivity and water entry or bubbling pressure
Cover	Land use, agricultural practise and hydrologic condition	Tillage influences on soil properties Landuse and treatment practises influence on soil properties Ground cover (live or mulch) influences on surface properties
Storage:		
Soil	Initial abstraction assumed to be 0.2(S)	Assumed infiltration prior to surface ponding
Surface	Included with initial abstraction	Estimated soil surface storage as influenced by topography, land use and tillage
Interception	Included with initial abstraction	Estimated interception storage by ground cover (live and/or mulch)

2.4 The proposed infiltration model

The proposed infiltration model is a physically based and dynamic model which provides the capability continuously to simulate one-dimensional, near surface soil water movement. During a storm, water supplied to the surface may either infiltrate or accumulate on the surface, and when a specified surface detention capacity is exceeded, runoff occurs. When precipitation ceases, water is redistributed by drainage and evaporation. This model is not spatially distributed, but all soil types in the subcatchment can be represented and variability of soil hydraulic properties may be further included into the model using a stochastic Monte Carlo method.

This section will examine the mathematical definition, the structure, the data requirements, the stochastic implementation, and the programming details of the physically based infiltration model. This model is based upon that developed by Anderson (1982). It should be noted that all parameter units in this section are metric.

2.4.1 The mathematical model

The law governing the flow of water through a rigid, homogeneous, isotropic, and isothermal porous media is described by a nonlinear Fokker-Planck equation. This is derived from two equations, Darcy's law, and the principle of continuity.

Darcy's law is based upon the more general Navier Stokes equation governing flow of a viscous incompressible Newtonian fluid. It states that the flow of water through a porous medium is proportional to the hydraulic gradient and the conductivity:

$$v = -K \nabla \phi \tag{38}$$

Where:

v - macroscopic vector velocity of water ($m\ s^{-1}$)

$\nabla\phi$ - gradient of total potential (metres) in 3-dimensional space

∇ - denotes $\frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$

and:

$$\phi = \Psi - z \qquad (39)$$

Where:

z - gravitational potential, depth from surface where downwards is positive (metres)

Soil pores are highly irregular, tortuous, and intricate. Flow through pores is limited by constrictions and occasional dead ends. Actual geometry and flow patterns are therefore far too complicated to be described in microscopic detail and hence this detail is ignored. The conducting body is treated as though it were a uniform medium with flow spread out over the entire cross section, solid and pore space alike. Thus discharge is expressed as a macroscopic vector velocity.

Childs and Collis-George (1950) confirmed experimentally that Darcy's law holds for flow in unsaturated soils, but in a slightly modified form, where K and Ψ are functions of the soil moisture content (θ).

$$v = -K(\theta)\ \nabla\phi \qquad (40)$$

$$\phi = \Psi(\theta) - z \qquad (41)$$

The general behaviour of $\psi(\theta)$ is now fairly well established. The principle of continuity states that the difference between the inflow and outflow per unit time is equal to the rate of change in storage. The continuity equation is given by:

$$\frac{\partial \theta}{\partial t} = -\nabla v \tag{42}$$

Where:

t - time (seconds)

Combining equation (42) with equation (40) gives:

$$\frac{\partial \theta}{\partial t} = \nabla (K(\theta)\nabla\phi) \tag{43}$$

Rewriting equation (43) in one dimension, for vertical flow, where z is the vertical distance taken downward as positive gives:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} (K(\theta) \frac{\partial \phi}{\partial z}) \tag{44}$$

Substituting equation (41) into equation (44) gives:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} (K(\theta) \frac{\partial}{\partial z} (\psi(\theta)-z)) \tag{45}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} (K(\theta) \frac{\partial \psi}{\partial z} (\theta))-\frac{\partial K}{\partial z} (\theta) \tag{46}$$

Equation (46) is equivalent to the Richards equation. To solve this equation for unsaturated conditions, the hydraulic conductivity function $K(\theta)$ has to be defined. Values of unsaturated hydraulic conductivity vary with soil moisture content and are very difficult to measure in the field, these data will not therefore be available for the ungauged catchment. It is therefore necessary to derive the hydraulic conductivity function numerically.

The theory which underlies this numerical derivation has been developed by Childs and Collis-George (1950), Marshall (1958), and Millington and Quirk (1959, 1960, 1961) and has been reviewed more recently by Gardner (1974). Childs and Collis-George (1950) were the first to relate the permeability of a porous medium to its pore size distribution. Flow is determined by the pore radii and by the probability of continuity of pores of different radii. The pore size distribution is assumed to be reliably described by the soil moisture characteristic curve. The infiltration model which is developed here uses the following relationship which has been established by Millington and Quirk (1959), and developed by Campbell (1974) and Jackson (1972). The relationship is described by:

$$K_i = K_s(\theta_i/\theta_s)^p \frac{\sum_{j=i}^{m}((2j+1-2i)\Psi_j^{-2})}{\sum_{j=1}^{m}((2j-1)\Psi_j^{-2})} \qquad (47)$$

Where:

K_s - saturated hydraulic conductivity (ms^{-1})
θ_s - saturated soil moisture content ($m^3 m^{-3}$)
m - number of equal sized increments of moisture content
p - a constant, the pore interaction term

In the original Millington and Quirk derivation the pore interaction term was assumed to be 4/3. However, Jackson (1972) determined that a value of unity for this constant allows a more accurate determination of the hydraulic conductivity function over a greater range of soils and unity has therefore been adopted for use in this study. More recently, Rajab et al (1982) have found that for a sandy soil for example, a value of 0.3 is most appropriate. Throughout this study a value of unity has been used.

Several points concerning the application of the Millington and Quirk method are relevant to this application, and will therefore be made.

1 Millington and Quirk (1961) stressed that in theory the method is inappropriate for soils which display anisotropy. In these circumstances, the probability of continuity cannot be ascertained from the pore size distribution and porosity alone. However, many have recommended that the Millington and Quirk method does represent a satisfactory method for prediction of soil water behaviour in field soils (Klute, 1972; Green and Corey, 1971; Nielsen et al, 1973; Gardner, 1974). There remain those, who would maintain that the numerically derived conductivity functions are not similar to measured values (Carvello et al, 1976; Cameron, 1978).

2 To derive reliable results from the model, the soil moisture characteristic curve must be reliable, and should span a wide range of moisture values. The moisture curve should be a desorption curve; it has been observed that the pore size distribution is not well described by the wetting curve (Kunze et al, 1968).

3 The method is not reliable for fine materials with a wide range of pore sizes (Bruce, 1972; Farrell and Larson, 1972; Denning et al, 1974), or for swelling soils. It is suitable for soils with stable structures.

4 The use of a matching factor in the Millington and Quirk method is to be highly recommended, as this results in improvements of

predictions. A matching factor is an adjustment which causes calculated conductivity values to agree with some measured conductivity at a particular water content. In general, saturated hydraulic conductivity values are used although for fine textured soils, Bruce (1972) found that a closer fit could be obtained with a measured conductivity value in the soil suction range 0.1 to 0.3 bar.

5 The number of equal intervals (m, in equation 47) into which the soil water characteristic is divided was found by Kunze et al (1968) to affect the prediction of the hydraulic conductivity function. Ten classes was found to be optimal.

The Richards equation is a nonlinear partial differential equation to which exact solutions are available only for specific inital and boundary conditions. To solve equation (46), it is necessary to convert the mathematical model into a form which can be solved approximately by digital computer. After Hillel (1977), the equations are converted into explicit finite difference equations and solutions are defined at discrete points in space and time. Inaccuracies due to approximation by finite differences can be made very small by the proper use of the method. In any case, errors are usually outweighed by inaccuracies in the specification of subsurface hydrological parameters. An explicit method, otherwise known as a forward difference method, uses coefficient and variable values at the beginning of a time step to predict values of dependent variables at the end of the time step.

Modelling of one-dimensional unsaturated and saturated soil water flow is a two stage procedure; firstly, the reduction of the flow system to a nonlinear partial differential equation, and secondly, the approximation of this nonlinear partial differential equation as a finite difference equation. If (E_x) is the exact solution to the nonlinear partial differential equation, (e_x) the exact solution to the finite difference equation, and (num) the numerical solution of the finite difference equation, then there are three requirements which any numerical method must fulfil:

1 The solution must be stable. Numerical errors (e_x-num) incurred in the solution of the finite difference equation must be small.

2 The solution must be convergent. Truncation error ($E_x - e_x$), incurred in the replacement of a continuous domain by a finite number of space and time points, must also be small. As the spatial and temporal increments become smaller, the solution must approximate the true solution.

3 The method must be computationally manageable.

The explicit solution fulfils the third criteria, it is a simple algorithm, but it does not display the best convergence or stability characteristics. It is usually only conditionally stable and convergence depends upon small time and space increments. Consequently, a large number of computations are necessary. As a check on stability, throughout the simulation, a mass water balance calculation is repeated to identify whether numerical errors are large, and if so, to identify where they become a serious problem. The mass water balance calculation is described by the following equation:

$$BAL = \theta_{end} - \theta_{init} - ci + ce + cd \qquad (48)$$

Where:

Bal - numerical error ($m^3 m^{-3}$)

θ_{end} - total water content of soil profile ($m^3 m^{-3}$) at end of simulation

θ_{init} - initial total water content of entire profile ($m^3 m^{-3}$)

cI - cumulative infiltration ($m\ s^{-1}$)

ce - cumulative evaporation ($m\ s^{-1}$)

cd - cumulative drainage ($m\ s^{-1}$)

If the value of (BAL) increases as the simulation proceeds, then either the time increment or the cell dimensions have to be reduced. In practice, the spatial and temporal increments must be kept small.

2.4.2 Basic structure of the infiltration model

In order to apply the mathematical infiltration model which has been described in the previous section, each major soil type in the catchment is represented as a soil column. The structure of the soil column is indicated in figure 16. It is divided into up to three layers; each is permitted to have different hydrological properties. All layers are further divided into cells, and flow between the midpoints of each cell is simulated under both saturated and unsaturated conditions. Detention capacity, expressed as an equivalent depth of water on the soil surface, has to be exceeded by rainfall excess before runoff begins. When precipitation ceases, this store is depleted by infiltration and evaporation. Detention capacity is the only model parameter which is not a measurable characteristic. It is not physically based, but represents the net effect of vegetation, interception, litter interception, and surface detention. Its value also reflects the antecedent moisture conditions of vegetation and litter. The model can accomodate dynamic changes in model structure; it allows water tables and perched water tables to develop and fluctuate through time.

2.4.3 Data requirements

The data which are required by the infiltration model are indicated in table 13. The soil hydrological characteristics are parameters which may not be commonly available for the ungauged catchment, but it is suggested that the series of charts and regression equations which were developed by Brakensiek and Rawls (1983) for the ungauged application of the Green and Ampt infiltration model may prove very useful in deriving the soil hydrological parameters required by the Richards equation, and to allow the routine use of the infiltration model for the ungauged catchment (Anderson and Howes, 1984; Anderson et al, 1985; Anderson and Howes, in press).

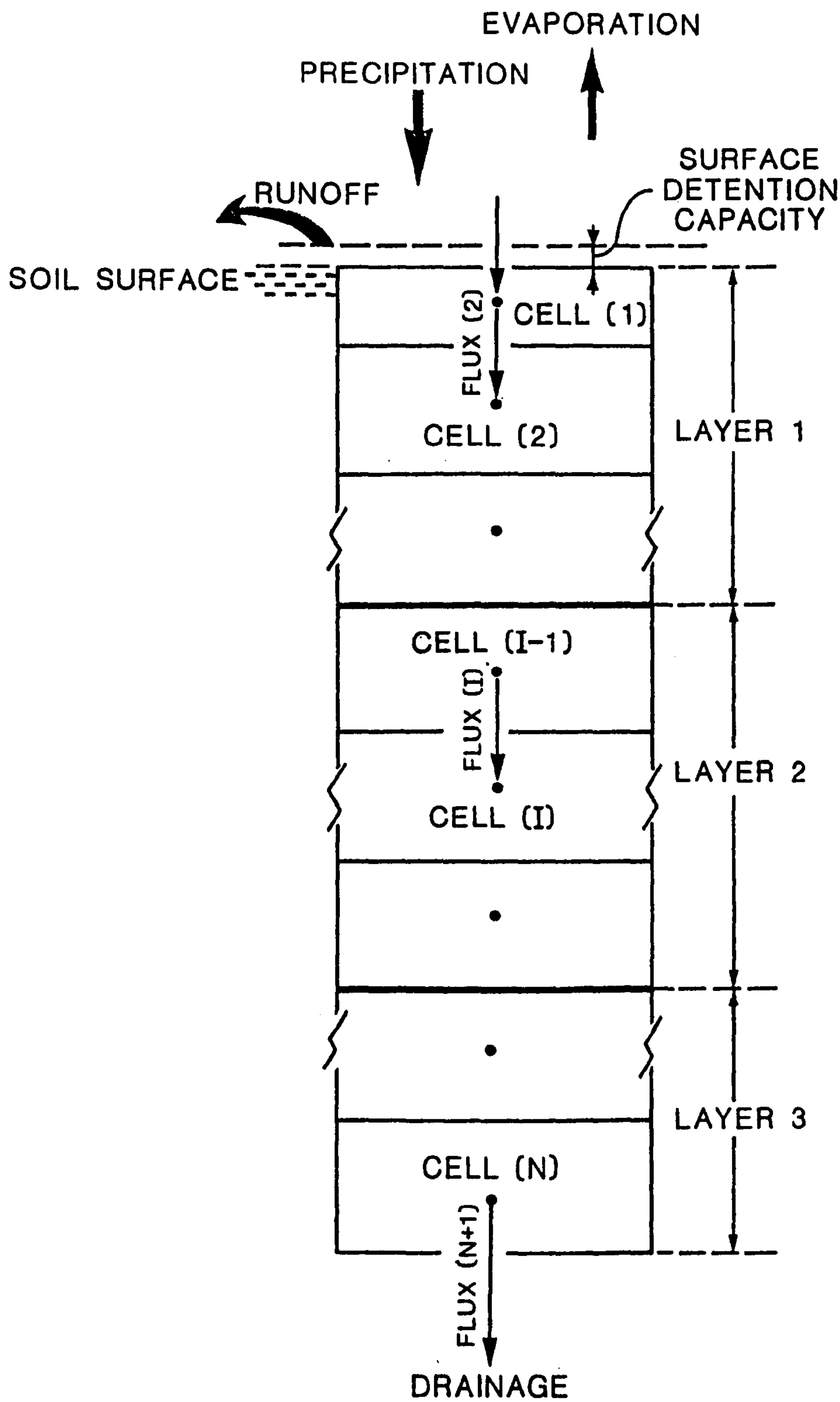


Figure 16: Basic structure of the infiltration model

Table 13: Data requirements of the infiltration model

Soil profile hydrological characteristics

For each layer:
- soil water content at saturation (m^3m^{-3})
- saturated hydraulic conductivity (m^3s^{-1})
- soil moisture characteristic curve (a maximum of 20 observations) (moisture content in (m^3m^{-3}), suction in (metres))

For each cell:
- initial soil water content (m^3m^{-3})

Soil profile dimensions

- total number of cells in column
- number of cells in layer 1
- number of cells in layer 2
- thickness of each cell (metres)

Surface conditions

- detention capacity (metres)

Precipitation

- rainfall data time increment (hours)
- rainfall data for each time increment (hours)
- rainfall start time (hours)
- rainfall stop time (hours)

Program controls

- iteration time for simulation (seconds)
- simulation start time (hours)
- simulation stop time (hours)
- number of profiles for the catchment area

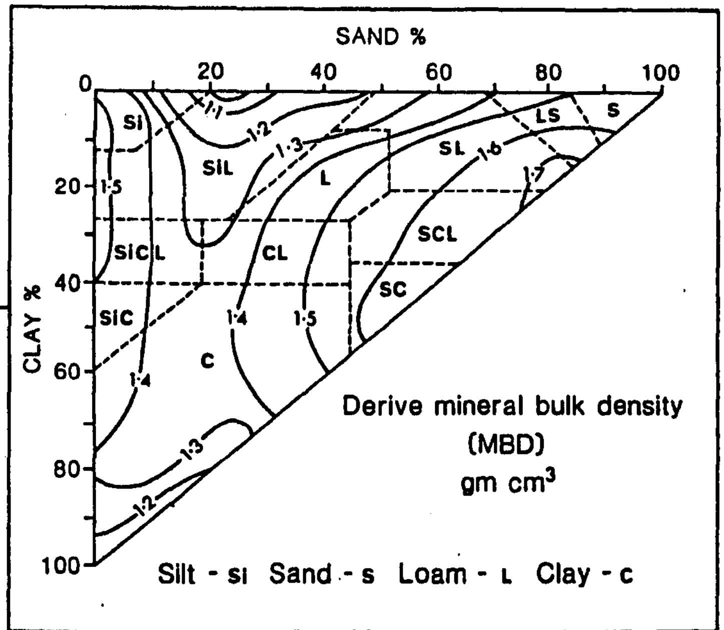
The charts and regression equations were developed from simulations based upon approximately 5,000 soil data sets in the United States, and represent average soil conditions prior to a particular agronomic practice. Figure 17 indicates that information concerning the percentage sand, clay, and organic matter of a soil is all that is required to derive the moisture contents corresponding to a broad selection of suction values. Soil texture data are used to derive the mineral bulk density, these together with the percentage organic matter are used to determine soil bulk density, and all are then used in the regression equations to provide the moisture content at a number of specified suction values. The soil water potential at air entry is derived from a table published by Rawls et al (1982) and which is reproduced in part in table 14, and this provides an additional point for the soil moisture characteristic curve. Figure 18 illustrates the two charts from which values of saturated hydraulic conductivity and saturated moisture content can be derived relating to the soil's percentage of clay and sand.

2.4.4 Stochastic infiltration model

It has been stressed in section 1.5 that one of the major problems in applying the infiltration equation to a catchment is the spatial variation of the soil's physical, and therefore hydrological, properties. This variability leads to a lack of confidence in a deterministic model and thus a stochastic approach can additionally be adopted. Such a framework has been introduced into the infiltration model in an attempt to incorporate estimates of known spatial variability within a soil type, and to establish its consequences upon the predicted hydrograph. Thus a probability distributed model (subsection 1.5.2) has been developed.

The variability of the five soil hydrological properties necessary to operate the model: detention capacity, the soil moisture characteristic curve, saturated soil moisture content, saturated hydraulic conductivity, and initial soil moisture conditions, is described by conventional statistics. Each is considered to be an independent random

% sand
% clay
%org. matter



Evaluates soil bulk density (SBD)

$$SBD = \frac{100}{\frac{\%org.\ matter}{0.224} + \frac{100-\%\ org.matter}{MBD}}$$

Table used to derive Θ for each given Ψ using the regression equation :

$$\Theta = a_i + b_i(\%sand) + c_i(\%clay) + d_i(\%org.matter) + e_i(SBD)$$

Matric Potential - Bars	a	b	c	d	e	R^2
-0.20	0.4180	-0.0021	0.0035	0.0232	-0.0859	0.75
-0.33	0.3486	-0.0018	0.0039	0.0228	-0.0738	0.78
-0.60	0.2819	-0.0014	0.0042	0.0216	-0.0612	0.78
-1.0	0.2352	-0.0012	0.0043	0.0202	-0.0517	0.76
-2.0	0.1837	-0.0009	0.0044	0.0181	-0.0407	0.74
-4.0	0.1426	-0.0007	0.0045	0.0160	-0.0315	0.71
-7.0	0.1155	-0.0005	0.0045	0.0143	-0.0253	0.69
-10.0	0.1005	-0.0004	0.0044	0.0133	-0.0218	0.67
-15.0	0.0854	-0.0004	0.0044	0.0122	-0.0182	0.66

Suction - moisture curve

Figure 17 Derivation of soil moisture characteristic curve from soil texture information

Table 14: Bubbling pressure classified by soil texture (adapted from Rawls et al, 1982, table 2)

Texture class	Sample size	Bubbling pressure (metres)
Sand	762	0.15
Loamy sand	338	0.21
Sandy loam	666	0.30
Loam	393	0.40
Silt loam	1206	0.51
Sandy clay loam	498	0.59
Clay loam	366	0.56
Silt clay loam	689	0.70
Sandy clay	45	0.79
Silty clay	127	0.77
Clay	291	0.86

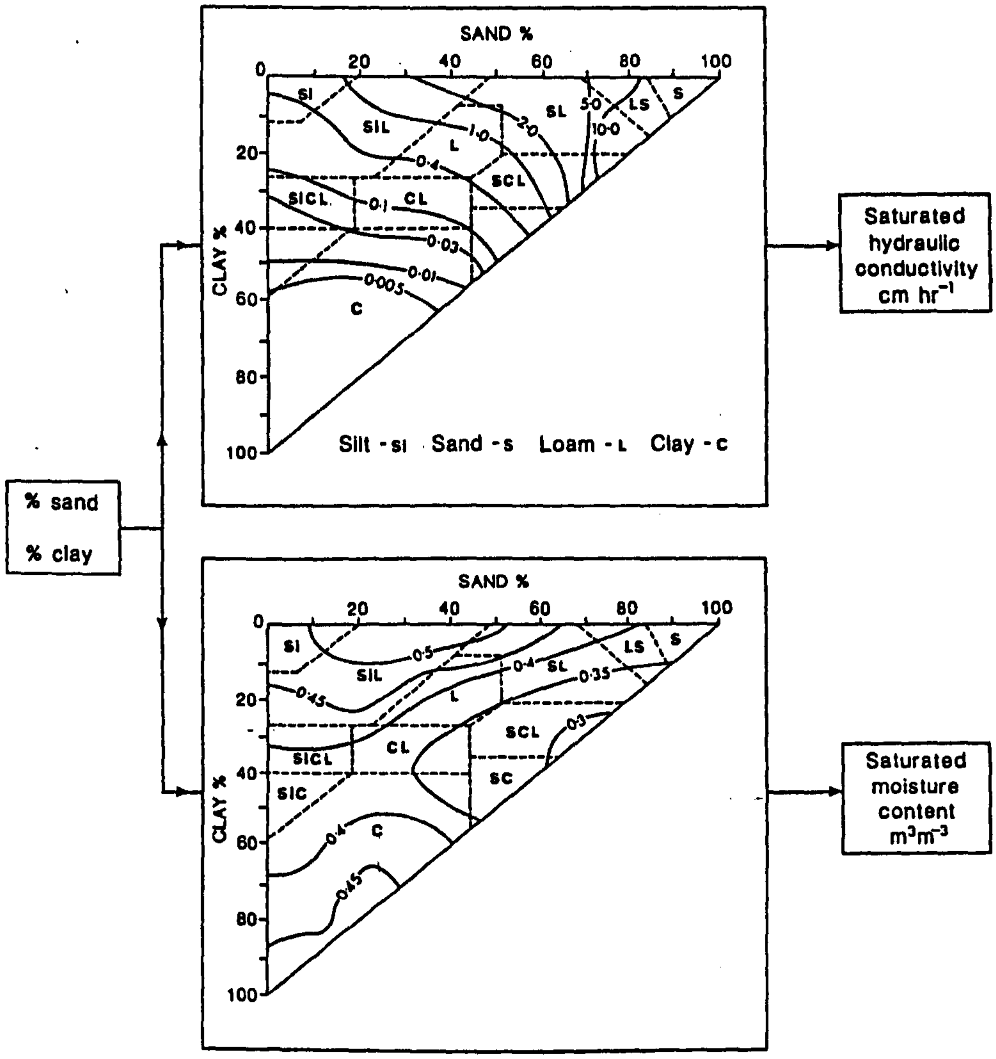


Figure 18: Derivation of saturated hydraulic conductivity and saturated soil moisture content from soil texture information

variable and may be described by a suitable probability density function, derived from the literature (table 5). Rogowski (1972), Nielsen et al (1973), Coelho (1974), Baker (1978), and Russo and Bresler (1981b) have all provided evidence for log-normally distributed hydraulic conductivity. Other soil hydrological properties have been shown to display normal distributions (Nielsen et al, 1973; Rogowski, 1972; Russo and Bresler, 1981b). For this model, detention capacity was assumed to be normally distributed. It is acknowledged that catchment variability is not without spatial structure, but insufficient geostatistical information describing the characteristics of this structure is currently available for incorporation into the model. The assumption of independence will, however, provide predictions for the ´worst case´ situation; incorporation of spatial autocorrelation would decrease model output variance.

A procedure has been built into the infiltration model program which generates random values for the five soil hydrological parameters. The random number generator which has been used is a NAG (Numerical Algorithms Group) routine, reference number G05DDF, which returns a ´psuedo-random´ number from a normal probability distribution. There are three requirements to generate the random numbers in the infiltration model for each of the five input parameters:

1 The specification of a probability distribution.
  This is an expression of the relative likelihood of different parameter values.
2 The mean and standard deviation.
  The mean reflects the average value of the parameter and the standard deviation reflects the magnitude of error of the estimate.
3 The ranges of the physically allowable parameter values.
  These reflect some knowledge of the possible field ranges.

The NAG routine, G05DDF, is therefore called which returns the random value from a normal distribution provided that the mean and standard deviation are specified. The normal distribution in this algorithmn is given by:

$$p(x) = \frac{1}{\sqrt{(2\pi\sigma)}} \exp\left(\frac{-(x-\bar{x})^2}{2\sigma^2} \right) \qquad (49)$$

Where:

$p(x)$ - probability of (x)
σ - standard deviation
$\bar{x}$ - mean

As neither the normal nor log-normal distributions are bounded at the tail, there is a small probability of randomly generated values assuming negative values. Checks are therefore performed on the generated values, to ensure physical consistency. Total independence of the five parameters can not be assumed. Many checks which are enforced involve adjusting parameter values according to the values which have been generated for the other parameters.

The procedure for the stochastic variation of each of the five parameters will be discussed in turn.

Detention capacity

The random number generated from the normal distribution is constrained only by the condition that it cannot assume a value of less than zero. If the generated value does fall below this limit, it is set to zero.

Saturated soil moisture content

As the infiltration model is capable of simulating up to three hydraulically different layers, three different means and standard deviations may be entered into the program. The value is generated randomly for each layer from the normal distribution and then checked against the largest moisture value in the soil moisture characteristic curve. If the saturated soil moisture content is smaller than this value then it is reset equal to the largest moisture values in the curve.

Soil moisture characteristic curve

As for the saturated soil moisture content, up to three curves may be input to the model, one for each layer in the soil column. For each curve, for each tension, the moisture content is allowed to vary according the the normal distribution with a given mean and standard deviation. The procedure begins with the smallest moisture content. If this randomly generated value is less than zero then its value is set to 0.001. Random numbers are then generated for the other moisture contents. If any randomly generated value is less than or equal to the previous values, then it is set equal to the value plus a small increment. Thus reverse gradients are not allowed to develop in the curve. The largest moisture value is finally compared to the saturated soil moisture content as has been described.

An alternative method would be to randomly generate one moisture value, to then find the difference between the randomly generated moisture value and the mean, and finally to increment all moisture values by this difference. However, this procedure would not allow variation in the standard deviation with soil moisture tension and there is evidence in the literature that this may be the case (Nielson et al, 1973; Cameron, 1978).

Saturated hydraulic conductivity

Again, a mean and standard deviation can be entered for each layer. As this parameter is considered to be log-normally distributed, for each layer, the logarithm of the mean is taken. This is used to generate the random number from the normal distribution and the antilogarithm of the generated number is then taken. There are no checks on the generated value.

Initial moisture content

The randomly generated value for initial moisture content is generated for each cell in the soil column. Each is compared to the saturated soil moisture content for the relevant layer. If it exceeds this value, then it is set equal to the limit. The initial moisture content is also checked against the moisture values in the soil moisture characteristic curve for the layer. To calculate unsaturated conductivity values, the initial moisture content of each cell must lie within this range.

2.4.5 Description of the program which implements the infiltration model

The basic structure of the computer implementation of the infiltration model is illustrated in figure 19. It has been written in Fortran 77 so as to be compatible with HYMO. The program is structured into three parts: the initial, dynamic and terminal sections:

Initial section In this section, arrays are dimensioned, variables initialized, and the data are read in and checked for inconsistencies; error reports are provided where necessary. If a stochastic application of the model is required, randomly generated values for each of the five soil hydrological properties are derived from the mean and standard deviation which the user has supplied. The Millington and Quirk method is used to determine the conductivity functions for each layer. A print out of the initial conditions, and details of the simulation may be output to specified peripherals if required by the operator.

Dynamic section This contains the sequence of operations which are performed repeatedly at each time step. This time interval is specified by the operator. An internal clock is set and updated as the simulation proceeds. For each cell, the moisture content is known from the initial conditions provided by the user, or from the calculations performed in the previous time interval.

Firstly, the soil suction which corresponds to the moisture content of each cell is derived from a linear interpolation procedure from the known points on the moisture characteristic relation; unsaturated hydraulic conductivity is derived by similar means from the hydraulic conductivity funtion. The hydraulic potential of each cell is given by equation (41), where z represents the depth from the surface to the midpoint of each cell.

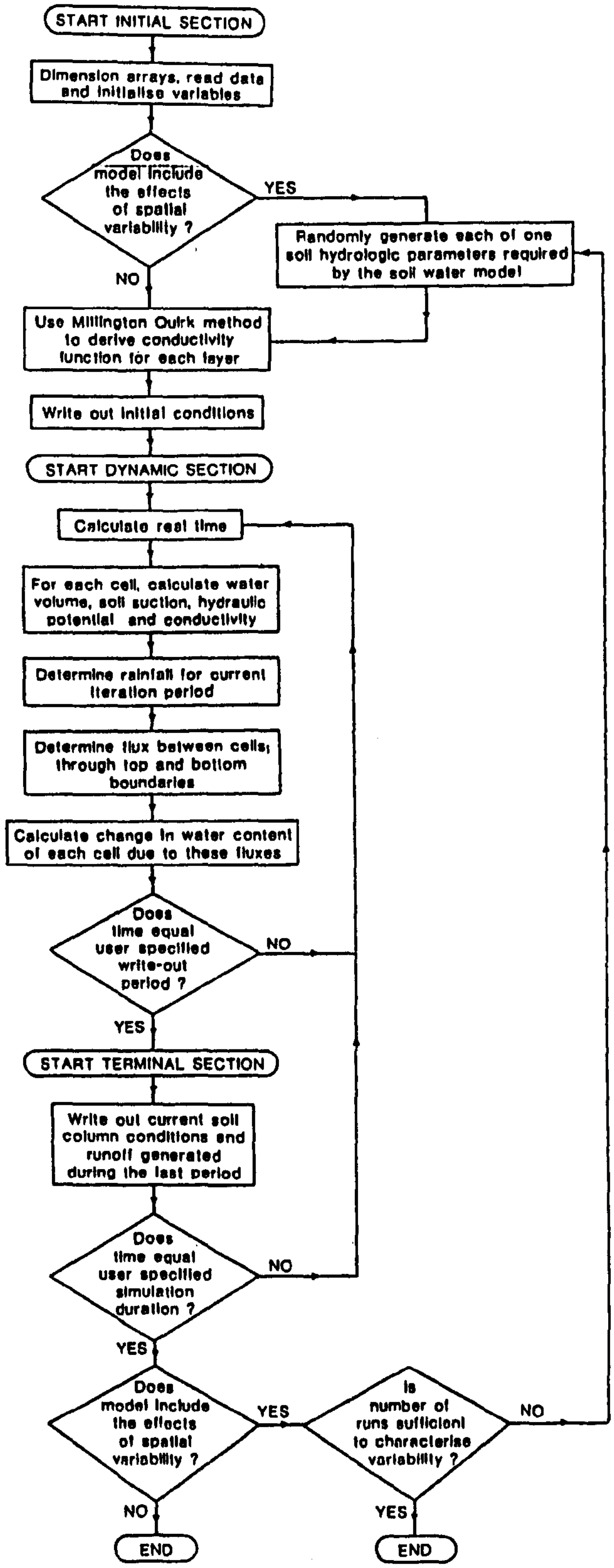


Figure 19: Structure of the infiltration model program

Rainfall for the current time step is derived from the rainfall data input.

The flux into each cell (v_i), except for the surface cell, is given by Darcy's law, which in discrete form and for the flux from cell (i-1) into cell (i) becomes:

$$v_i = (\phi_{i-1} - \phi_i)(\bar{K}/l) \tag{50}$$

Where:

- l - distance between the midpoints of the two cells (i) and (i-1) (metres)
- $\bar{K}$ - average hydraulic conductivity for flow through the boundary ($m\ s^{-1}$) between adjoining cells, weighted according to thickness, and given by the following equation:

$$K = \frac{(K_{i-1} T_{i-1}) + (K_i T_i)}{T_{i-1} + T_i} \tag{51}$$

Where:

- T_i - thickness of cell (i) (metres)

The flux out of the bottom cell is assumed to be equal to the hydraulic conductivity of that cell, although other bottom boundary conditions could be specified.

The determination of the flux into the top cell is crucial for this application, and deserves closer attention. Firstly, the infiltration capacity (i_c) is derived from the characteristics of the top cell (i=1), and is calculated from the following equation:

$$i_c = \frac{0.5(\ -\theta_{i=1})(K_{s(layer\ 1)} + K_{i=1})}{T_{i=1}} \tag{52}$$

Where:

$K_{s(layer\ 1)}$ - saturated hydraulic conductivity of top layer ($m\ s^{-1}$)

The precipitation excess is then calculated and cumulated throughout the simulation duration. If this is positive, it represents excess water which is stored on the surface.

If it is raining, then evaporation is set to zero. Provided that the rainfall rate is smaller than the infiltration capacity, and there is no surface detention, the flux into cell 1 equals the rainfall rate. If these conditions are not met, then the flux equals the infiltration capacity. If there is surface detention, and this exceeds the detention capacity, then runoff occurs. If it is not raining however, runoff is set to zero and the evaporation rate (e) in mm hr^{-1} is derived from the following simple isothermal relation:

$$e = \frac{e_{max} \sin(2\pi t)}{86400} \tag{53}$$

Where:

t - time from sunrise (seconds)
e_{max} - maximum midday evaporation rate (mm hr^{-1})

(Between 18:00 and 06:00, (e) is set to 1/100th of e_{max}.)

If there is water remaining on the surface from the storm, water moves into cell 1 at a rate equal to the infiltration capacity. The evaporation and infiltration which occurred during the iteration period are then deducted from the surface detention. It there is no water, water may move out of cell 1 at a rate equal to the evaporation rate.

When the fluxes have been determined, the moisture content of each cell is recalculated in consideration of these fluxes and is given by:

$$\theta_i' = \theta_i + \frac{(v_i - v_{i-1})}{T_i} \tag{54}$$

Where:

θ_i' - new moisture content of cell (i)

The program then checks the time on its internal clock against the time interval for which a printed copy the soil column conditions is required (this will normally equal the time interval of rainfall data). If the two do not agree, the program returns to the beginning of the dynamic section; if they do, then the program proceeds to the terminal section.

<u>Terminal section</u> In this section, a write out of current conditions of each cell in the soil column, the precipitation, and any surface storage, runoff or evaporation which may have occurred is performed. Another time check is then performed, and if the simulation has not been completed, the program loops back to the dynamic section to continue simulation. If it has been completed, and a deterministic application is being made, the program terminates. If the stochastic model is being applied, the complete simulation will be repeated with different randomly generated input variables, until sufficient runs have been made to characterize the variability of the hydrograph response.

2.5 HYMO2

The infiltration model, which has been described in section 2.4 and which includes the option as to whether or not a stochastic application is required, was developed on a mainframe, the Honeywell 6800 under Multics. This model has been fully incorporated into HYMO to replace the curve number procedure and to produce HYMO2. Figure 20 indicates very simply the manner in which the infiltration component has been inserted into the hydrograph computation procedure which has been described in subsection 2.1.1. The basic lumped infiltration model merely replaces the curve number model, and the subroutine continues as before. The stochastic model does produce more than one hydrograph and these are all stored. All hydrographs produced may then be plotted out, or alternatively, statistics which describe the characteristics and the variability of the predicted hydrographs may be calculated. The newly modified HYMO, HYMO2, including the deterministic infiltration model, has been successfully ported onto a 32 bit microcomputer, the Hewlett Packard 9816 which contains a 68000 microprocessor, 3/4 M byte of RAM, and a 15 M byte hard disc for program and data storage. The stochastic version of the model has not been transferred onto the microcomputer as a suitable random number generator has not been developed, and due to the very great demands which repeated execution of the model places on the computer. The source program occupies 65 K bytes of memory on the HP 9816 and the compiled code and data areas, 90 K bytes of memory.

In application of HYMO2 for runoff prediction to a catchment or subcatchment, the area does not have to be assumed to be homogeneous. Soil conditions can be represented by more than one soil column. Soil hydrological information for each of the major soil series or groups in the area is used to set up a soil column (figure 16) for each soil type. In order to combine the relative contributions of runoff provided by each of the soil types, the complete storm is applied to each of the soil columns, and the incremental runoff produced by each is weighted according to the percentage area of the catchment occupied by that particular soil type. These relative contributions are then summed to

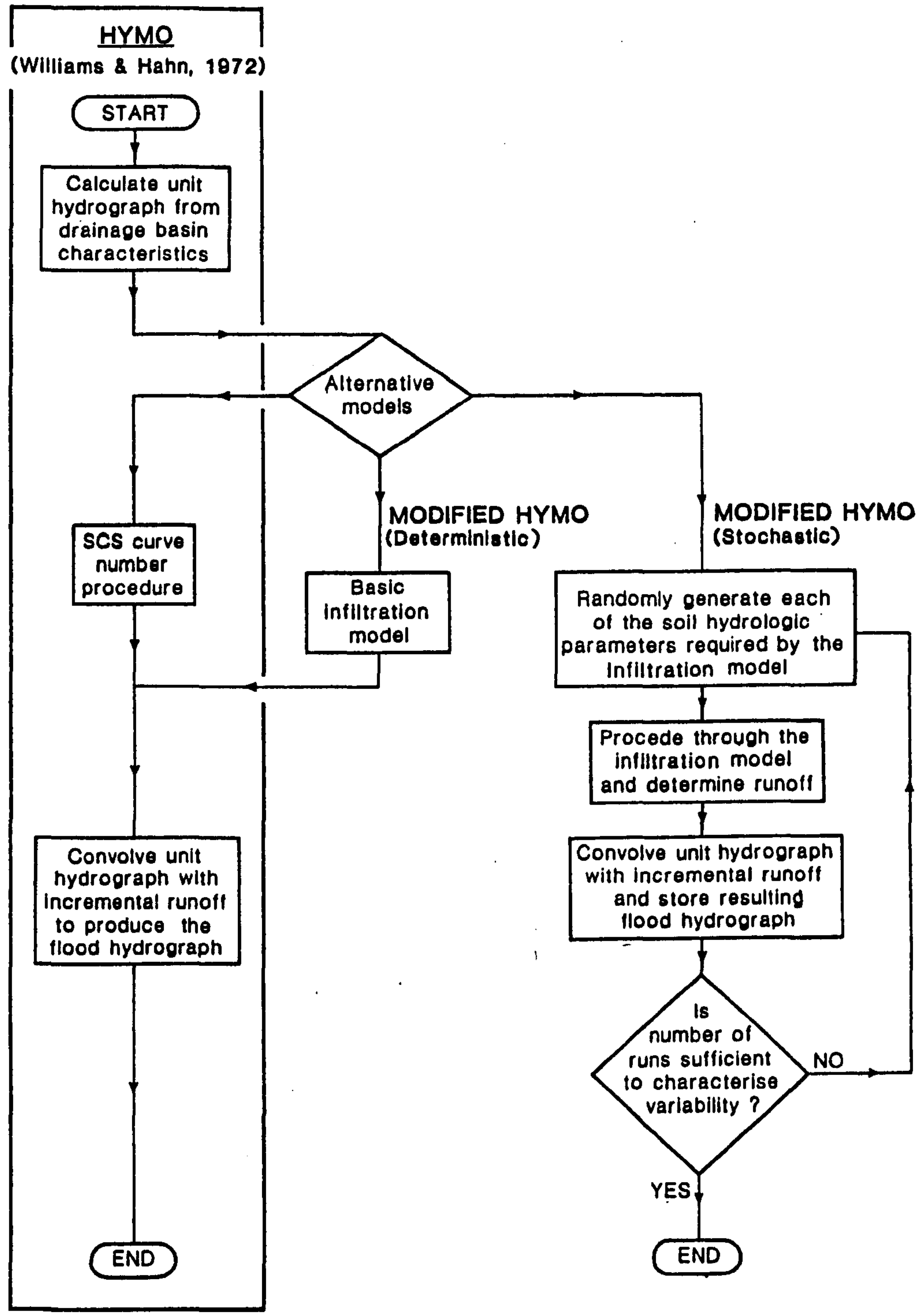


Figure 20 Three alternative procedures for the derivation of a flood hydrograph for a sub-catchment

produce the total runoff volume derived from the subcatchment. It should be stressed however, that the relative locations of each soil type are not explicitly taken into account.

Any decision concerning the number of soil columns which will be used to describe the subcatchment area will have to trade the advantages of a more complete representation of the conditions with the disadvantages of an increase in data acquisition and computer requirements and will depend upon the user's requirements.

The following three chapters will present what is hopefully a critical, and where possible, objective evaluation of HYMO2 which has been described in this chapter. As suggested in section 1.3 and figure 2, a three stage model evaluation strategy has been undertaken. There are a number of questions which each stage of the evaluation must address. These will now be presented:

<u>Mathematical model evaluation</u> (Chapter 3)

1 Are the assumptions of the infiltration model reasonable for the intended ungauged and operational application? Could more realism (hysteresis or soil crusting for example) be incorporated into the infiltration model, whilst maintaining its utility for the proposed application?
2 Are the hydrological processes which are known to occur in the catchment system adequately and correctly expressed by HYMO2? What is the likely significance of neglecting certain hydrological processes which are not included in the model?

<u>Computerized model verification</u> (Chapter 4)

1 Does the infiltration algorithm operate correctly over a range of conditions?
2 How sensitive is HYMO2 to the soil hydrological parameters?
3 Does the explicit finite difference method provide satisfactory results?

Operational validation (Chapter 5)

1 Is the Brakensiek and Rawls empirical information for deriving soil hydrological parameters suitable for the application of HYMO2 to the ungauged catchment? What is the effect of the choice of iteration period for the solution of the infiltration equation upon predictions provided by the model?

2 How well does HYMO2 predict the discharge hydrograph of a storm event?

3 Does application of the stochastic implementation of HYMO2 which incorporates an estimate of the spatial variability of soil hydrological properties significantly improve hydrograph predictions?

These questions will be examined in the following three chapters.

3

Model evaluation I: Mathematical model evaluation of HYMO2

The importance of a well structured and thorough methodology for the evaluation of any computer simulation model has been emphasized in section 1.3, and this chapter, chapter 4 and chapter 5 are all concerned with such an evaluation of HYMO2, the modified model which has been presented in chapter 2. This evaluation must be carried out in the context of the proposed application, and as has been stressed in section 1.3, it is important for three reasons:

1 To allow the reliability of the information provided by the mathematical hydrological model to be assessed for the ungauged catchment.

2 To enable the mathematical model which has been proposed in chapter 2 to be tested, and thereby to be accepted or rejected. If there is to be progress in hydrological modelling, the relative contribution of every mathematical model presented must be judged. The status or merit of each model must be determined as objectively as possible.

3 To provide the user with an understanding of a model's capabilities and limitations. This will enable the user to apply the model advantageously and to provide meaningful interpretations of predictions. The user needs to know the effort required to set the model up, the results which will be obtained, the skill required to interpret results, and the computational requirements involved.

It is important that two additional points which were made in section 1.3, be emphasized again. These must be borne in mind during the model evaluation which is documented in this and the following two chapters and indeed are relevant to any mathematical model evaluation.

Firstly, the process of model evaluation need not adhere to a strictly positivist approach, based purely upon empirical testing. It can, and indeed should, include a broader series of techniques designed to test the operation of the model for a range of conditions, and a full discussion of the model basis and relevance for the application.

Secondly, no model of the natural environment can ever be completely validated. Assessments must be based upon a limited number of experimental frames.

The three stage model evaluation strategy which was proposed in subsection 1.3.3, and illustrated in figure 2, is adopted here. This comprises mathematical model validation, computerized model verification, and operational validation.

Mathematical model validation is the first stage of model evaluation, and will be considered in this chapter. It is basically a subjective procedure, based on discussion, and aimed at establishing that the assumptions made during model formulation are reasonable, and that the model adequately reflects the essential features and behaviour of the real system which are relevant for the application in mind. The problem of mathematical model validation arises since in any modelling exercise, various approximations to reality are made, restrictions are placed upon model operation, and certain factors believed to be unimportant are neglected. No model is completely comprehensive. As a model's predictions are conditional upon the authenticity of its assumptions, it is important that the model be accurately defined and disparities between the model and real world clearly specified.

It is important to examine whether HYMO2 represents a model appropriate for the prediction of the outflow hydrograph of an ungauged catchment, for a single storm event, and in an operational context. In order to address the two questions, raised in section 2.5, which concerned the mathematical validity of HYMO2, this chapter will be divided into two sections: firstly, a discussion of the assumptions of the infiltration model and secondly, a discussion of the hydrological processes which HYMO2 incorporates.

3.1 Discussion of the assumptions of the infiltration model

Are the assumptions of the infiltration model reasonable for the intended ungauged and operational application? Could more realism (hysteresis or soil crusting for example) be incorporated into the infiltration model whilst maintaining its utility for the proposed application?

In discussion of this question, three points can be made. These are concerned with firstly, the applicability of Darcy's law, secondly, the simplifying assumptions made by the infiltration model, and thirdly, the suitability of simulation techniques. Each of these are now considered in more detail.

Firstly, in application of the Richards equation (the basis of the infiltration model), Darcy's law is assumed to be appropriate. Darcy's law makes the following six assumptions.

1 The soil water is assumed to behave as a viscous, incompressible Newtonian fluid. Deviation from this will be most likely to occur in conditions of low hydraulic gradients, and for flow through small pores.

2 The Reynolds number of the flow of soil water is assumed never to exceed unity; the flow is laminar. This will apply to flow in silts and finer materials, but nonlaminar flow may occur in coarser sands and gravels.

3 The soil through which flow occurs is assumed to be rigid. Darcy's law only applies to the flow of soil water relative to soil properties. Complications due to swelling colloids for example, are not taken into account.

4 The effects of pressure differences at the soil and air interface are assumed to be neglible. It is assumed that displaced air is able to move through the soil profile with neglible resistance, and that air pressure remains constant throughout. This may be justified by the small viscosity of air relative to water and by assuming that air can escape through large pores which remain partially open during infiltration. There are, however, numerous examples where air is trapped by infiltrating water, and where air pressure builds up in advance of the wetting front.

5 The soil system is assumed to be isothermal.

6 It is not feasible to know the microscopic details of the internal soil geometry. It is assumed therefore, that consideration of the soil at an aggregate level (where measurement of conductivity, potential and moisture content, and calculations of discharge, refer to a scale which is larger than the size of the individual pore) is appropriate.

It has been demonstrated experimentally that Darcy's law is appropriate to soil water flow in many natural sediments. Exceptions do occur in extremely fine grained clays and in some soils which contain clay fractions (Olsen, 1966). These deviations are caused by nonNewtonian behaviour of soil water due to clay and water interactions. Swartzendruber (1968) emphasized that for a clay soil, greater than proportional response of flow velocity to hydraulic gradient for both saturated and unsaturated flow is displayed. For sands and silts however, Darcian behaviour is considered to be appropriate.

As Hillel (1975) very clearly stated:

> ".. the soil is a highly complex system. It consists of solid components, mineral and organic, irregularly fragmented and variously associated and structured in an intricate geometric pattern. The solid matrix is not rigid or inert, but interacts with the fluids which permeate the inter-particle voids. These fluids are air of varying composition and water with various solutes. This complex is practically never in a state of static equilibrium, as the soil heats and cools, wets and dries, swells and shrinks, disperses and flocculates, cracks and disintegrates, and undergoes chemical changes. Finally, the soil serves as the habitat for a great variety of microscopic and macroscopic organisms which multiply and decay and interact in ways almost too complex to describe." (Hillel, 1975, p121)

No theory can encompass this degree of detail, but attention can be drawn to examples of more complex infiltration models which are appropriate for situations where the assumptions of Darcy's law are not upheld. A number of examples may be given by way of illustration.

Infiltration into a deforming porous medium, where the continuity equation must be solved for both the water and soil, has been studied by Philip (1969). Where the flow of air cannot be displaced, the basic infiltration theory has been extended to two phase flow which takes account of resistance to air flow and compressibility of air. Much of this theory has been developed in petroleum engineering. In hydrology, it has been documented by Morel-Seytoux (1973), Morel-Seytoux and Noblanc (1973), Noblanc and Morel-Seytoux (1972), Raats (1973), and Philip (1975). Infiltration into nonisothermal systems involves the simultaneous solution of heat and moisture transfer equations and has been attempted by Philip and de Vries (1957) and De Vries (1958). Elzeftawy (1980) reviewed certain of these models.

The theory does exist which describes most types of complex infiltration behaviour. However, it is important to stress that these models are far too demanding in terms of data, computer resources, and experience of user, to be relevant for the ungauged and operational application which is of issue here. For this application, there is more interest with the discharge behaviour at the catchment outflow point rather than with providing an understanding of the detailed soil water movement at a point.

The second point which can be made in discussion of this question concerns further simplifying assumptions which are made by the infiltration model which has been developed in section 2.4. The model assumes that infiltration can be considered to be one dimensional (soil water only moves vertically downwards), and that the effects of surface crusting and hysteresis on the infiltration process can be ignored. Again, there are models which deal with infiltration in more than one dimension, Philip (1967) for example presented the equations and solution for infiltration in two and three dimensions. The effects of surface crusting (which acts to decrease infiltration with time) has been incorporated into infiltration models at a number of levels of complexity by Hillel and Gardner (1969, 1970) and Whisler et al (1979). Hysteresis has also been incorporated into infiltration models (Mualem and Dagan, 1972; Mualem, 1979).

Modelling of these more complex components of infiltration is indeed possible, but application of these models to the ungauged catchment is not feasible due to their extensive data and computational needs. The full implications of complications such as hysteresis and surface crusting for the infiltration and runoff process has not yet been fully established. What is certain however, is that predictions, for this ungauged catchment application, will not necessarily be improved by incorporating more realism into the infiltration model, when the error involved in specifiying or generating the required soils data from a minimum of catchment information will be so great; where the computer resources limit the accuracy of numerical solution of the necessarily more complex equations; and where an inexperienced user, unfamiliar with the theory and the model, has to take what are characteristically subjective and ill-defined decisions concerning application and parameter estimation.

The infiltration model which has been suggested in chapter 2 does allow for infiltration into stratified, or layered soils, from variable rainfall intensities; it allows for evaporation from the soil surface; and it does incorporate a measure of detention capacity (expressed in terms of depth of surface water). Two assumptions are made in the representation of detention capacity Firstly, it is assumed that no evaporation occurs during precipitation. There are empirical studies which suggest evidence to the contrary (Zinke, 1967; Leonard, 1967; Helvey, 1967), that evaporation rates can attain maximum potential rates during the start of precipitation. Secondly, the model assumes that detention capacity does not vary with precipitation intensity. These simplifying assumptions made in the representation of detention capacity may introduce error into the model predictions, and will depend in part upon the model's sensitivity to this parameter. This is an issue to which attention will be turned in chapter 4.

The third point which is germane to this discussion has been made in the hydrological literature by Hillel (1977). He draws attention to a limiting factor in the use of simulation techniques to simulate the behaviour of any natural phenonemon. In a simulation model, only one process can be allowed to operate at any one period of time. Simultaneously occuring events must be assumed to be independent. Each event is controlled only by the conditions at the start of each time step. Processes (the fluxes) may affect variables describing the system, but their values are not updated until the beginning of the next time step. It has to be assumed therefore, that the order in which they are considered is not critical. It is accepted that no computer simulation model, even when based upon the most complete theory would exactly reproduce the behaviour of the prototype system in this respect.

The ungauged and operational model application which is the subject of this thesis does not require a full, or detailed understanding of the infiltration process which occurs at a small scale. It is therefore suggested that the infiltration model which has been proposed does make reasonable asumptions which enable flood hydrograph predictions to be made routinely, and by an inexperienced user, for a substantial catchment area. No more realism could be incorporated into the model whilst retaining its utility for the intended application. Indeed, no more realism is considered to be necessary.

The use of a simplified infiltration model and simulation techniques for predicting catchment runoff will introduce error into predictions. This will probably be negligble however, in comparison to the amount of error which is introduced by parameter estimation for the ungauged catchment.

3.2 Discussion of the hydrological processes which are incorporated in HYMO2

Are the hydrological processes which are known to occur in the catchment system adequately and correctly expressed by HYMO2? What is the likely significance of neglecting certain hydrological processes which are not included in the model?

There is substantial empirical evidence for a variety of different storm runoff producing mechanisms on the catchment slope (Dunne, 1978), and indeed of highly complex and interchanging flow paths of runoff contributing to the stream discharge (Knisel, 1973). Woolhiser (1982) stressed that any drop of rain water may follow an infinite number of pathways to catchment outflow.

At one end of this range of runoff producing mechanisms, Hortonian overland flow occurs (Horton, 1933). This overland flow is generated where the precipitation rate exceeds the infiltration capacity of the surface soils. All water reaching the channel has failed to infiltrate the soil surface at any point in the catchment. This is found where soils have low infiltribility, where high rainfall intensities are experienced, or during snowmelt conditions. It is thus characteristic of agricultural areas, unvegetated surfaces, semi-arid areas, and arid areas.

At the opposite end of the spectrum of runoff producing mechanisms, subsurface flow occurs (Hursh, 1936). Water, which infiltrates the soil surface, moves laterally through the upper soil layers towards the channel. (This should not be confused with base flow, which involves a much deeper percolation of water which enters the permanent groundwater flow and contributes to channel baseflow between storms.) Storm runoff reaches the channel completely by subsurface flow, and does not appear on the soil surface. This flow is characteristic of soils with high conductivities, macropores, and which display profile inhomogeneities along which lateral flow is encouraged. Thus it is typical in well vegetated and forested watersheds which are undisturbed, and where organic litter protects the soil structure.

Between these two extremes, saturation overland flow occurs. The soil surface layers saturate from infiltration and subsurface flow from upslope. Saturation overland flow comprises a combination of direct precipitation onto saturated areas (water which does not infiltrate), and return flow (subsurface flow which emerges from the soil). It is found characteristically in partial areas of the catchment where topography is convergent, where there are shallow soils, where rain is impeded by low permeability layers, and which are subjected to extended rainfall periods. The dimensions of these partial areas are not time invariant, but expand and contract according to the antecedent and prevailing hydrological conditions.

HYMO2 only models Hortonian overland flow and saturated overland flow where the water table is allowed to build up from below, with no subsurface flow contributions from upslope. Soil water movement is considered in one dimension only. All water entering the soil is effectively lost to soil storage, drainage or evaporation. In view of the very large variety of complex processes which occur in the catchment, HYMO2 is simplified, and it would thus be reasonable to expect a good scatter of model results.

There are many mathematical models which do attempt to model subsurface flow contributions to the flood hydrograph. A few of these will be outlined briefly. Water movement in the soil occurs in two domains, micropores and macropores. Soil water movement in the soil micropores is slower and only under very specific conditions is this thought to provide significant contributions to stormflow reponse. Freeze (1972a) suggested that only where convex hillslopes feed deeply incised channels, and where saturated hydraulic conductivities are high that subsurface flow will significantly contribute to streamflow. Beven (1982b) however did stress that the right conditions are often to be found in forest soils, and that under these conditions, rapid flows are possible. Flow in macropores is however significant to the hydrograph response on a catchment slope. Rapid flow through cracks, pipes, or macropores can provide significant contributions to the streamflow storm discharge in sufficient time to contribute to the storm hydrograph rise. In some catchments, macropores can act to extend the dynamic contributing area by allowing rapid subsurface flow from upper slope areas to reach channels (Wipkey, 1967; Gilman and Newson, 1980). These structural voids which may be due to soil animal activity, biological, or physical processes, enable water to by-pass the less conductive soil matrix. They are believed to be most effective during or just after very heavy rains (Edwards et al, 1979; McCaig, 1982), when a supply of water can be maintained to the pipes and where they are continuous and open at the soil surface.

Most theoretical models of subsurface flow have dealt with flow within the micropore domain. The most complex model was provided by Freeze (1971, 1972a, 1972b) and Stephenson and Freeze (1974). A three-dimensional, transient, saturated, and unsaturated subsurface flow model is coupled to a one-dimensional, gradually varying, unsteady, channel flow. The equations are solved by finite difference and application is restricted by computer resources to simulation of a single event, and for a single hillslope feeding a single channel. A less complex two-dimensional application of the Richards equation has been provided by Neuman (1973) and Nieber (1979, 1982). Simpler models than this have been designed for practical application. Beven (1981, 1982a) produced a subsurface flow model based on a kinematic approximation which was found to be, for a range of conditions of practical interest, as accurate as the more theoetically complete Dupuit-Forchheimer equation. Sloan and Moore (1984) outlined and compared five subsurface flow models which range in complexity and found the simple storage models provided by Beven (1981, 1982a) to be more accurate than the complex two-dimensional solution to the Richards equation.

Modelling of subsurface soil water flow in macropores has received far less attention. It has been emphasized that the Richards equation was designed for application to homogeneous soil cores where flow is laminar and where the assumptions of Darcy's law are upheld. Application to heterogeneous field soils often results in an underprediction of the rates of water movement, as it does not take the more rapid flow through macropores into account. Direct application of Darcy's law to field situations may therefore not be appropriate. There have been a number of models which have attempted to model pipeflow and four possible methods have been suggested.

Firstly, the soil is considered, quite realistically, as comprising two domains, the micropore and macropore. Flow through the micro pore is modelled by Darcy's law and bulk flow through the macropores is treated with more appropriate flow equations. Flow within the two systems is considered seperately and the interactions between the two are then taken into account. This type of model has been used by Edwards et al (1979), and Beven and Germann (1981). Armstrong (1983) suggested a practical model based on this idea of two domains, where the equations of flow in each is empirical, rather than physically based.

Secondly, Darcy's law can be modified for turbulent flow. Whipkey (1967) discussed a number of these attempts, but they have not on the whole been very successful as they have been developed from laboratory data, and only apply in limiting porous conditions. Application to field soils is not realistic. Thirdly, Darcy's law can be applied but with 'effective' soil parameters. These parameters may be radically different from those expected of the soil. Finally, the application of statistical models has been proposed. Armstrong (1983) posed the question of whether a deterministic model is at all appropriate for such a variable and complex soil system. A statistical regression model was derived by Germann and Beven (1981) to be used as a 'first approximation' to predict macropore discharge.

In view of the complexity of the hydrological processes, and of the availability of more complex physically based models which do attempt to model these processes, is HYMO2 not to be considered a little too simplified? Subsection 1.4.1 outlined some of the technical problems associated with the application and development of physically based models of hydrological processes. These models require very detailed data; not just in terms of quantity, but more importantly, in terms of quality. They suffer problems with the numerical solutions to the flow equations. To avoid the conditions of instability and nonconvergence, simplifying assumptions often have to be made. Successful application of these solutions requires a good deal of computing resources, and demands experience and familiarity of the user. Their application to a catchment situation is limited to detailed instrumented research catchments, and even in these situations, either considerable data generation is required or resort to calibration is necessary. Thus, an ungauged and operational model is necessarily restricted to the form of that outlined for HYMO2.

A further simplification of HYMO2 should also be discussed. A dimensionless unit hydrograph is used to convert the rainfall excess provided by the infiltration model, to a surface runoff hydrograph which is characteristic of the catchment or subcatchment area. The unit hydrograph procedure makes the following assumptions:

1 The catchment response to unit rainfall excess is assumed to be time invariant. The catchment always responds to a given rainfall event in a similar manner and is independent of antecedent catchment conditions, and season.

2 Rainfall is assumed to be uniformly distributed in space and time.

3 The catchment response to a storm is linear; the ordinates of direct runoff hydrograph are directly proportional to rainfall excess.

4 The time distribution of direct runoff due to effective rainfall of unit duration is constant.

Certain weaknesses of the unit hydrograph method can therefore be defined. Errors will be introduced by the assumptions of time invariance and linearity, and by the dependence on the similarity of behaviour between the catchment under consideration and those for which the unit hydrograph was synthesized. However, one can only speculate at this stage as to the potential reliability and validity of the model for particular situations. This must be examined in more detail during application to actual catchments.

There is no consensus as to the implications of the linearity assumption on model predictions. Laurenson and Mein (1975), Diskin (1982), and Betson (1964) have all pointed to evidence for highly nonlinear catchment behaviour, and Freeze (1972a) stressed that as well as there being no physical reason for a linear catchment response, neither is there any reason to expect a consistent nonlinear response. Certain authors do feel that a linear assumption will adequately approximate the behaviour of the real system (Nash and Foley, 1982).

However, certain strengths of the unit hydrograph can also be identified. The major advantage lies in its ease of application, and computational efficiency. It has been one of the most frequently used techniques in applied hydrology, and has been considered to be sufficiently accurate for a wide range of applications.

The alternative to a unit hydrograph technique is a fully distributed physically based model of surface overland runoff as described by the Saint Venant equations. Solution of these is attained by numerical methods, although in certain conditions, the kinematic approximation to the momentum equations may be appropriate. This approximation greatly simplifies the solution. The unit hydrograph method was retained because of its inherent relevance to the specific application. There is little to be gained in the application of a distributed model for situations where distributed data are not available. There is no alternative which is viable for this application. There is evidence in the literature that the unit hydrograph method still remains the most commonly used method for the translation of catchment runoff to channel hydrograph as the more complex and demanding alternative models do not provide significant improvements to predictions, and are consequently not worth the extra effort which is involved in using them.

HYMO2 does not attempt to model all known components of the catchment hydrological system. State of the art models which involve a more realistic and complete representation of the prototype system are not at all suitable or appropriate to achieve the objectives of the ungauged and operational application. HYMO2 remains simplified, but consistent with the intended application.

It has been argued in this chapter, that the mathematical definition of HYMO2 can be considered to be valid within the context of the ungauged and operational application. It has been stressed that the requirements of these applications place very severe contraints upon the level of model complexity which can be achieved, and hence upon the scientific rigour of the model. It is suggested that HYMO2 achieves an appropriate balance between a realistic and practical hydrological model.

Stage two of model evaluation, computer model verification, is documented in the following chapter.

4

Model evaluation II: Computerized model verification of HYMO2

It is important to establish that the HYMO2 computer program is reliable. The majority of software errors are known to occur during translation of a mathematical model into computer code and it is important therefore that the mathematical model be correctly specified and that care be exercised during translation. Hence the second stage of model evaluation involves a series of techniques which are designed to ensure that the computer program actually carries out the logical processes expected of it, and that the hydrological procedures act rationally. The model is caused to go through a series of changes controlled by its structure and its behaviour should be similar to those changes which the real world would undergo in a comparable situation.

This chapter will address those questions concerning computerized model verification which were raised in section 2.5, and will therefore be divided into three sections: a verification of infiltration behaviour, a sensitivity analysis, and an examination of the accuracy of the finite difference method.

4.1 Examination of the infiltration behaviour predicted by the infiltration algorithm

Does the infiltration algorithm operate correctly over a range of conditions?

This first question is concerned with establishing that realistic infiltration behaviour is predicted by the model. Investigation of the behaviour of the infiltration model program has established the following points. Further consideration of predicted infiltration behaviour will be given during application of the model to actual catchments.

1 The model is internally valid (Hermann, 1967). No variance of output is exhibited if the model inputs are held constant, and the model is executed a number of times. The computer implementation of the infiltration model will exactly replicate predictions.

2 Hillel and van Bavel (1976) have established that the Millington and Quirk method, which is utilized in the infiltration model numerically to derive the hydraulic conductivity function, and which is described by equation (47), does provide realistic predictions for a range of hypothetical soil types. Their published data were used to test the implementation of the Millington and Quirk method which has been developed in this model and to establish that the same results would be derived. The soil moisture characteristic curves for typical sand, loam, and clay soils, which they used are provided in figure 21(A). The respective saturated soil moisture content and saturated hydraulic conductivity values for each soil are 0.44 $m^3 m^{-3}$ and 2.5×10^{-5} ms^{-1} for sand; 0.48 $m^3 m^{-3}$ and 0.7×10^{-5} ms^{-1} for loam; and 0.52 $m^3 m^{-3}$ and 0.2×10^{-5} ms^{-1} for clay. Figure 21(B) indicates the numerically derived hydraulic conductivity functions for the three soil types. These are indeed consistent with those published by Hillel and van Bavel (1976, p808) and thus the Millington and Quirk algorithm is considered to be correct.

3 The soils data provided by Hillel and van Bavel (1976) for the sand and clay soil types were used to investigate the relative saturation which develops at 10 cm depth after three hours of precipitation. Figure 22 indicates the results of this application and the soil moisture conditions which develop are seen to be consistent with the expected behaviour of that soil type for a range of initial soil conditions and storm intensities. For example, the higher

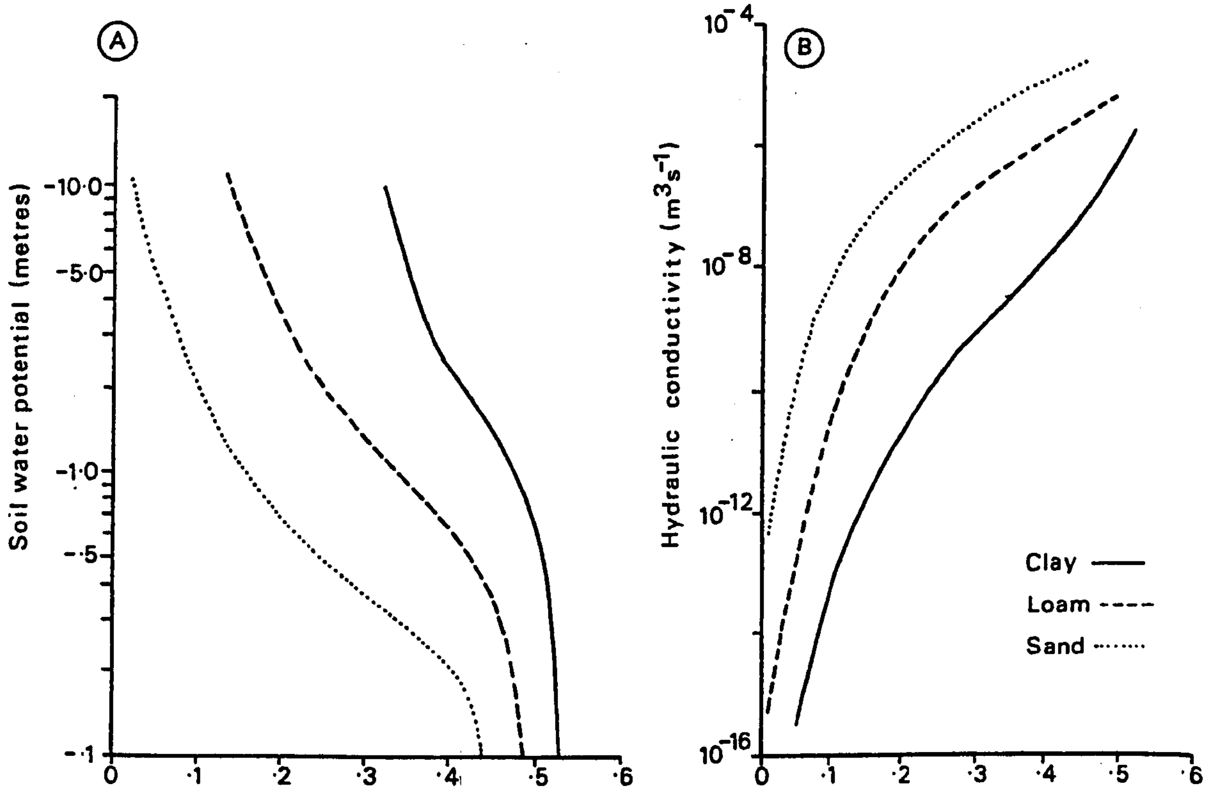


Figure 21: (A) Soil moisture characteristic curves and (B) the associated hydraulic conductivity curves derived from the Millington and Quirk method for 3 soil types

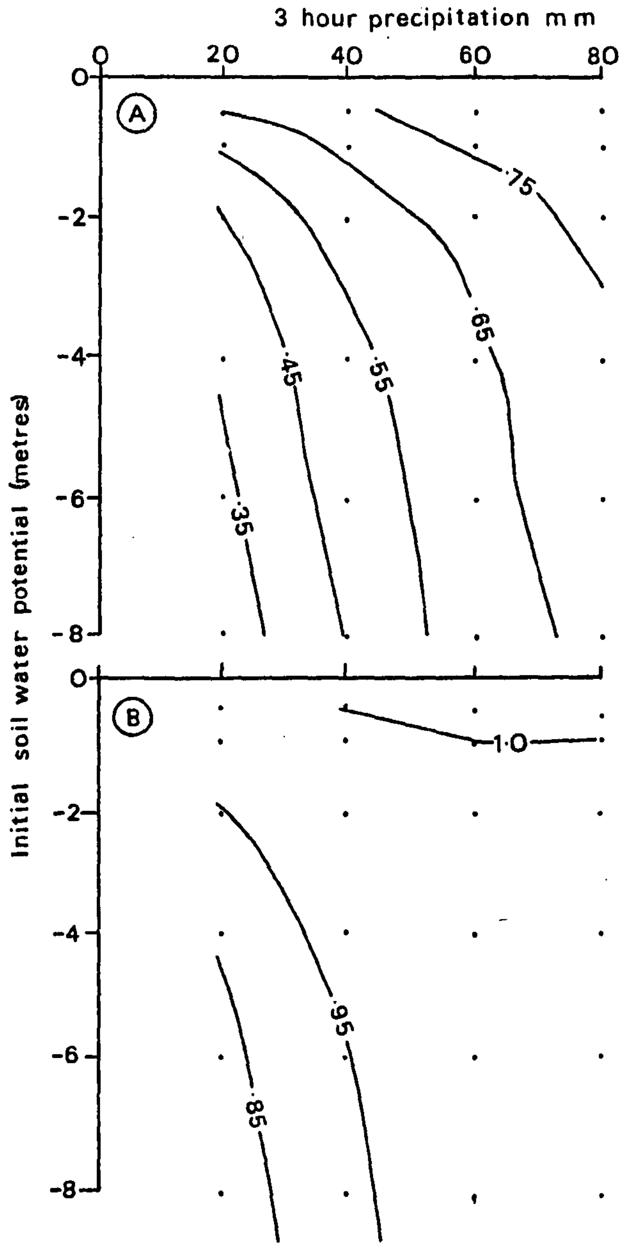


Figure 22: The relative saturation which develops at 10cm depth for a range of storm and initial soil water conditions for (A) sand and (B) clay soil

conductivity of the sand allows the applied water more rapidly to move through the profile and a greater relative saturation develops for the clay soil, near the surface.

4 Finally, the data provided by Hillel and van Bavel (1976) were also used to examine the nature of the soil moisture fluxes which occur at different depths within the sand and clay soil types. Figure 23 indicates that for these 2 soils, simulated behaviour is consistent with that expected by theory. Greater fluxes are experienced for the sand than for the clay, and for both soils, greater fluxes are experienced closer to the surface.

An initial examination has therefore revealed that for a range of simplified situations, the infiltration algorithm does predict infiltration behaviour which is consistent with theory.

4.2 Examination of the sensitivity of the predictions provided by HYMO2 to the soil parameter inputs

How sensitive is the modified model to the soil hydrological paramaters?

Sensitivity analysis is a "..modelling tool.." (McCuen, 1973, p38), which can be used to examine the effect of input data error on model predictions. This information is essential for guiding model application and is achieved by measuring the rate of change of the model output with respect to model inputs. Sensitivity analysis is a quantitative method of verifying a simulation model which does not require comparison to a particular data set, but which proceeds from the model itself.

Miller et al (1976) have pointed out that model evaluation has traditionally been postponed until such a stage has been reached in research when observed and simulated output can be compared. At this

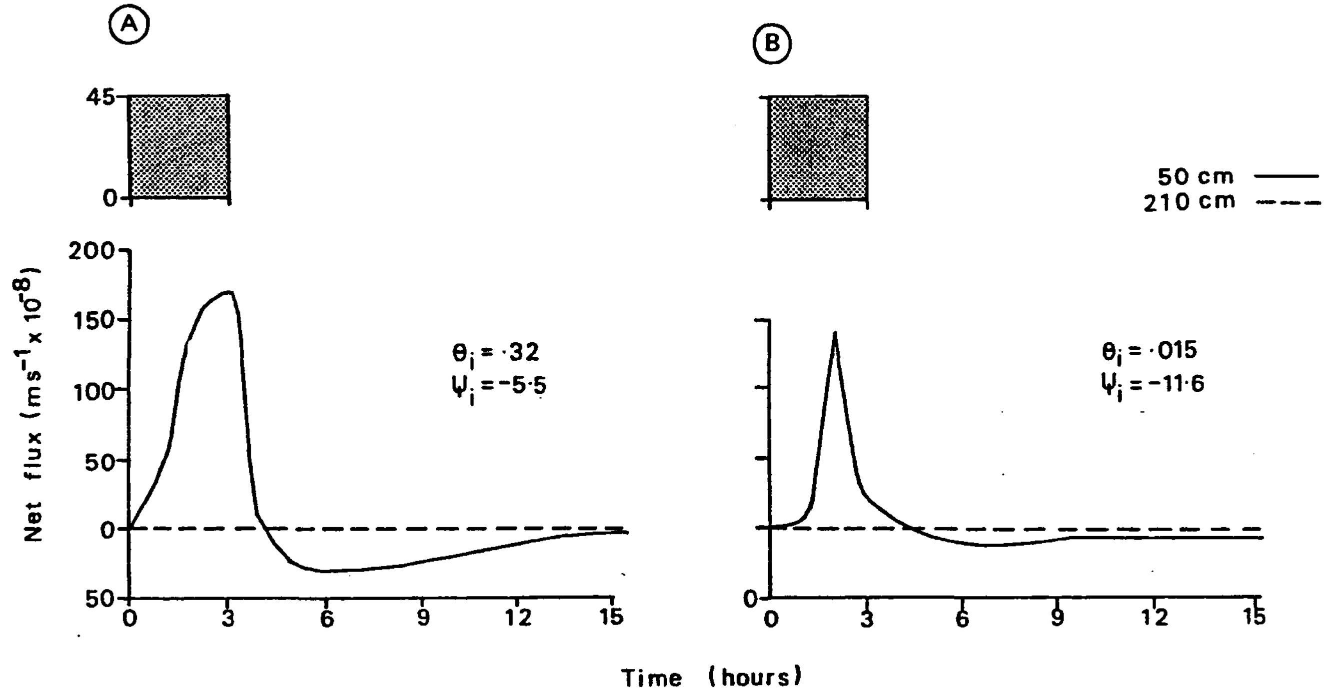


Figure 23 The net fluxes which occur during a storm at 50 and 210 cm depths for both (A) clay and (B) sand soils

stage however, large amounts of resources have already been committed to model formulation, often data have been derived from the field for calibration, and independent historical data gathered for model validation. Several authors have recently stressed the importance of applying a sensitivity analysis at a very early stage during model formulation (McCuen, 1973, 1976; Miller et al, 1976; Hornberger and Spear, 1981), and in this research programme, it is to be used at such a stage. However, it should be noted that many hydrological models are calibrated. A sensitivity analysis would, for these models, require that an adequate data base be already established for calibration. The infiltration model which has been proposed for this application contains physically based parameters. The sensitivity analysis can thus be carried out quite easily at an earlier stage during model formulation. Where necessary, values for the parameters can be derived from the literature.

Jones (1982) outlines two possible approaches to sensitivity analysis. The first follows a deterministic, and the second, a stochastic methodology.

The deterministic approach

The deterministic sensitivity analysis considers the influence of a small change in a parameter value on the model output. This is achieved by differentiation or by factor perturbation. The general mathematical definition of sensitivity and the two methods of computation which follow, are taken from McCuen (1973, 1974). Consider the general equation describing a system:

$$F_0 = x(F_1, F_2, F_3, \ldots F_n) \tag{55}$$

Where:

F_0 - model output
F_i - input parameters
n - number of input parameters

The change in model output resulting from a change in one factor (F_i), is given by:

$$x(F_i + \Delta F_i,\ F_j|_{j\neq 1}) = F_0 + \frac{\partial F_0}{\partial F_i}(\Delta F_i) + \frac{1}{2!}\frac{\partial^2 F_0}{\partial F_i^2}(\Delta F_i^2) + .. \quad (56)$$

If nonlinear terms are small in comparison with linear terms, equation (56) reduces to:

$$x(F_i + \Delta F_i, F_j|_{j\neq 1}) = F_0 + \frac{\partial F_0}{\partial F_i}(\Delta F_i) \quad (57)$$

Thus:

$$F_0 = x(F_i + \Delta F_i, F_j|_{j\neq 1}) - F_0 = \frac{\partial F_0}{\partial F_i}(\Delta F_i) \quad (58)$$

Equation (58) is the linearized sensitivity equation, which measures change in model output resulting from change in one model parameter. This can be extended to the case where more than one parameter is changed simultaneously.

The general definition of sensitivity is given by:

$$Sf = \frac{\partial F_0}{\partial F_i} \quad (59)$$

or alternatively:

$$Sf = \frac{[x(F_i + \Delta F_i, F_j|_{j \neq i}) - x(F_1, F_2, F_3, \ldots F_n)]}{\Delta F_i} \qquad (60)$$

Where:

S - sensitivity function of the factor F_i

For each factor, the sensitivity function can be derived, which estimates quantitatively the effect of that parameter upon output. This sensitivity function is not independent of the magnitude of the factor. To assess the relative importance of each factor therefore, the relative sensitivity function (R_S) has to be defined.

$$R_S = \frac{\partial F_0}{\partial F_i} \; \frac{\partial F_i}{\partial F_0} \qquad (61)$$

Equation (60) suggests two methods of computation.

1 Differentiating
The direct method of differentiating the relationship shown in equation (55) with respect to factor (F_i) has not been used extensively because the mathematical framework has not yet been sufficiently developed.

2 Factor perturbation
This is the most commonly used method. Sensitivity of the model output to changes in the input factor can be derived by incrementing the factor and computing the result of changes in the output. Use of

this method however, requires very extensive computational effort for a complete sensitivity analysis. This methodology was adopted by Smith (1976) and was referenced in section 2.2 to illustrate the sensitivity of HYMO to the SCS curve number procedure.

The stochastic approach

The second approach to the sensitivity analysis is a stochastic methodology. This is based upon the assertion that uncertainties in the model structure and data allow a meaningful analysis to deal with probabilities of behaviour. Model input parameters are randomly selected from probability distributions, which are a measure of the relative likelihood of different paramater values, according to a mean and standard deviation. The standard deviation is a measure of the amount of error associated with the specification of that parameter. Variation in model output relating to a much wider spread of data uncertainty can therefore be evaluated. This range typically covers the entire spread of physically realistic values.

This stochastic sensitivity analysis has been used specifically to determine whether or not HYMO2 which incorporates the infiltration model as a replacement for the SCS curve number procedure, and which requires more detailed soils information, is applicable to the ungauged catchment situation. The same program adaptations as those which incorporated stochastic spatial variability, and which were described in section 2.4.4, have been used. Specifically, the infiltration model requires five soil hydrological properties: detention capacity, saturated hydraulic conductivity, saturated soil moisture content, initial soil moisture content, and soil moisture characteristic curve. The sensitivity analysis is used to quantify the effect of uncertainty in estimates of these five parameters upon simulated outflow hydrographs. If the model proves to be highly sensitive to parameters which are not generally known to the required degree of accuracy in the ungauged catchment, then the infiltration model may not be suitable and either an alternative runoff prediction model could be explored, or the original SCS curve number procedure retained.

Detention capacity is the only model parameter which is not physically based. It represents the net effect of a number of watershed parameters and as such, it is not a measurable characteristic. Error is therefore associated with its estimation which means that it is very important to evaluate the effect of error of estimates of this parameter on model forecasts.

The infiltration model offers the modeller the capability of being able to define the soil antecedent moisture conditions on a cell by cell basis for the soil column (figure 16). This allows a much greater range of antecedent conditions to be specified than was the case for the curve number procedure. The only constraint which the model has is that the soil water content of each cell must be within the range of moisture values given in the soil moisture characteristic curve. (This is in order that the unsaturated hydraulic conductivities can be calculated for each cell.) It is important to establish the effect of error in the specification of inital moisture content on the simulated outflow hydrograph. For the ungauged catchment, there may not be sufficient data accurately to specify the initial conditions of each soil cell. If error in this parameter causes significant variation in simulated output, then this model may not be suitable for the ungauged catchment.

The soil moisture characteristic curve, saturated moisture content, and saturated hydraulic conductivity are used by the Millington and Quirk method to calculate unsaturated hydraulic conductivities. Error in their specification may therefore affect the accuracy of the hydraulic conductivity function, and consequently of infiltration behaviour.

Design of the sensitivity analysis

The sensitivity analysis has been designed to provide information as to the relative significance of each of the five soil hydrological parameters. The variation of the flood hydrograph is considered in terms of the coefficient of variation of its three characteristics: runoff volume, peak discharge, and time from storm start to peak discharge. The coefficient of variation is expressed as a percentage, it is dimensionless and therefore allows for comparisons. It is given by the following equation:

$$CV = \frac{\sigma}{\bar{x}} \cdot 100\ \% \qquad (62)$$

The structure of the sensitivity analysis has been organized based on the following four criteria:

1 Maintenance of simplicity.

One subcatchment only has been utilized in this analysis. It has an area of 32.5 square km, the main river length is 5.3 km, and it has a difference of elevation of 30.5 metres. The catchment is represented by a single soil column, a clay, which is vertically homogeneous. The soil moisture characteristic curve for the clay soil is given by Hillel (1977), saturated hydraulic conductivity for all three layers is 3×10^{-7} ms^{-1}, saturated soil moisture content is 0.525 m^{3} m^{-3}, and and initial soil moisture content is assumed to be uniform down the column and set to a high relative saturation (80%) to reduce the probability of no runoff. There is also empirical evidence that errors in the measurement of soil hydraulic properties are of far greater consequence for water contents near to saturation than for drier conditions (Skaggs and Khaleel, 1982). Detention capacity is assumed to be 0.005 metres.

2 Model predictions are likely to be more sensitive to some input parameters than to others.

Each of the five input parameters were varied individually to evaluate their relative importance, and finally all were varied together to determine the manner in which they interrelate and to determine the effect of total data input uncertainty.

3 Model predictions are likely to display greater sensitivity when variation in input parameters is increased.

Several levels of variation of input parameter error (standard deviation) were used to determine the effects of various magnitudes of parameter error.

4 Variation in model output is likely to depend upon storm intensity and duration characteristics as well as to the magnitude of variation in input parameters.

Rather than considering variation in model output for just one storm, nine different storms were used to determine the conditions under which the model may become more sensitive to data input error. The nine storms are illustrated in figure 24.

For each of the nine storms, each parameter was varied individually and the model executed 15 times. When all five parameters were varied simultaneously, at least 25 runs were required to reflect the variability. The distribution of outflow hydrographs was stored, and the mean, standard deviation, and coefficient of variation of the hydrograph characteristics were derived. It is fully appreciated that only 15 runs of the model for each storm condition might be rather too few a number from which to characterize variability, but 15 runs did require a significant period of time to execute on the computer. 20 to 30 runs were made for certain conditions and were found not significantly to alter the output variation. This greater number of runs was therefore used where greater variability in output was expected, to check on the calculations of output variability.

Several points can be drawn from the information derived from the stochastic sensitivity analysis. Firstly, for applications where each of the soil properties is varied individually and the remaining four are not varied at all, the following comments can be made.

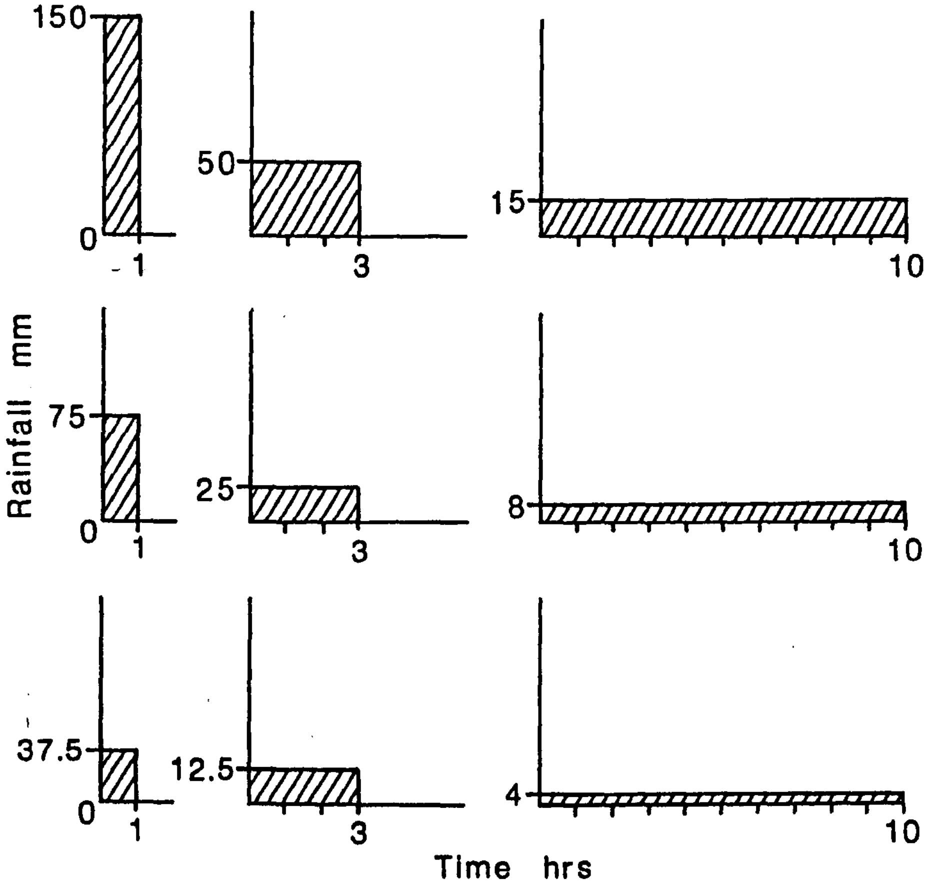


Figure 24: The nine storms used for the sensitivity analysis

1 No variation in outflow hydrographs is caused by variation in saturated soil moisture content.

The model is not sensitive to this parameter when it is varied alone.

2 No runoff is produced for the lowest intensity, longest duration storm except for the case where detention capacity is varied. In this case there is a probability of detention capacity assuming a value of zero.

This is illustrated in tables 15 to 18.

3 The magnitude of variability of the flood hydrograph is positively related to the magnitude of variation (or error) in the input parameters, but it is also strongly related to the storm characteristics.

Tables 15 to 18 indicate that, as would be expected, as the standard deviation of each input soil parameter increases, so does the variation of runoff volume, peak discharge rate, and time to peak. However, variation of the outflow hydrograph also increases as the storm intensity decreases and storm duration increases. Higher intensity storms of shorter duration can therefore be identified as conditions where sensitivity to data error is minimal.

4 In response to variation in each input soil parameter, the magnitude of the variation of runoff volume is very similar to peak discharge, but for many storm conditions, the time to peak does not vary.

There is very little variation of time to peak except for the case where the variation of saturated hydraulic conductivity is increased to 50%. This point is illustrated in tables 15 to 18.

Table 15: Sensitivity of the flood hydrograph to error in saturated hydraulic conductivity

CV of saturated hydraulic conductivity (%)	Total rain (mm)	CV of runoff volume (%)			CV peak discharge (%)			CV time to peak (%)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
0.3	150.0	0.5	0	0	0.1	0.4	1	0	0	0
	75.0	0	0	0	0.2	0.4	3	0	0	0
	37.5	0	4	-	0.3	2	-	0	0	-
3.0	150.0	1	2	8	1	2	7	0	0	4
	75.0	3	8	33	16	7	26	0	0	0
	37.5	4	16	-	4	14	-	0	0	-
50.0	150.0	77	69	75	54	70	71	54	59	54
	75.0	68	100	114	70	97	116	54	90	105
	37.5	100	54	-	97	55	-	83	53	-

CV coefficient of variation
\- indicates no runoff

Table 16: Sensitivity of the flood hydrograph to error in initial moisture content

CV of inital moisture content (%)	Total rain (mm)	CV of runoff volume (%)			CV peak discharge (%)			CV time to peak (%)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
5.7	150.0	2	5	4	2	4	3	0	0	0
	75.0	5	11	28	5	9	33	0	0	6
	37.5	13	45	-	13	45	-	0	11	-
57.1	150.0	6	15	32	7	15	23	0	0	6
	75.0	10	29	96	11	26	87	0	0	7
	37.5	47	71	-	44	66	-	0	55	-
100.0	150.0	6	11	28	6	10	23	0	0	5
	75.0	7	32	86	17	32	77	0	0	7
	37.5	53	120	-	55	129	-	0	131	-

CV coefficient of variation
- indicates no runoff

Table 17: Sensitivity of the flood hydrograph to error in detention capacity

CV of detention capacity (%)	Total rain (mm)	CV of runoff volume (%)			CV peak discharge (%)			CV time to peak (%)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
20	150.0	0.2	1	6	0.5	0.5	4	0	0	9
	75.0	1	2	27	1	1	14	0	0	4
	37.5	2	3	120	2	3	108	0	0	60
100	150.0	2	2	13	2	2	12	0	0	13
	75.0	6	4	55	5	4	42	0	0	10
	37.5	13	15	111	11	13	112	0	0	106
200	150.0	5	2	43	5	2	35	0	0	11
	75.0	10	8	83	10	8	72	0	0	7
	37.5	13	15	125	10	13	121	0	0	100

CV coefficient of variation
\- indicates no runoff

Table 18: Sensitivity of the flood hydrograph to error in soil moisture characteristic curve

CV of suction moisture curve (%)	Total rain (mm)	CV of runoff volume (%)			CV peak discharge (%)			CV time to peak (%)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
6	150.0	1	0	1	0.1	0.5	1	0	0	0
	75.0	1	2	50	0.3	1	5	0	0	0
	37.5	0	5	-	0.1	13	-	0	0	-
50	150.0	1	0.6	2	0.2	0.6	2	0	0	0
	75.0	0	0.2	23	0.2	1	5	0	0	4
	37.5	0	5	-	1	3	-	0	0	-
100	150.0	0.7	0	2	0.2	0.5	2	0	0	0
	75.0	0.2	0.2	6	0.4	1	4	0	0	0
	37.5	0	6	-	1	2	-	0	0	-

CV coefficient of variation
\- indicates no runoff

5 The predicted hydrograph exhibits greatest sensitivity to saturated hydraulic conductivity, it is less sensitive to initial soil moisture content and to detention capacity. It displays relatively little sensitivity to the soil moisture characteristic curve.

Figure 25 illustrates for all nine storms, the variation of the three hydrograph characteristics in response to a 50% variation in saturated hydraulic conductivity, 100% variation in initial soil moisture content, 100% variation in detention capacity, and 100% variation in soil moisture characteristic curve.

To illustrate this point, for a rainfall intensity of 25 mm per hour, over 3 hours, a coefficient of variation of 100% in the saturated soil moisture content causes no variation in the hydrograph. The same degree of variation in the soil moisture characteristic curve, detention capacity, and initial soil moisture content causes variation of runoff volume and peak discharge of 1% or less, 4%, and 32% respectively. No variation in time to peak occurs. However, only a 50% coefficient of variation of saturated hydraulic conductivity causes between 97% and 100% of variation of runoff volume and peak discharge, and 90% of variation of time to peak.

As table 15 illustrates, the hydrograph is highly sensitive to variation in saturated hydraulic conductivity. An increase in the variation from 0.3% to 50% produces quite significant increases in the variation of the hydrograph. This sensitivity may be due in part to the fact that the randomly generated saturated hydraulic conductivity values are not limited or constrained by any checks in the program (subsection 2.4.4).

Table 17 indicates the sensitivity of the model to variation in detention capacity. The coefficient of variation was taken up to 200% because of the high level of uncertainty associated with an estimated value of detention capacity. This table also shows that the magnitude of variability of runoff volume, peak discharge and time to peak is

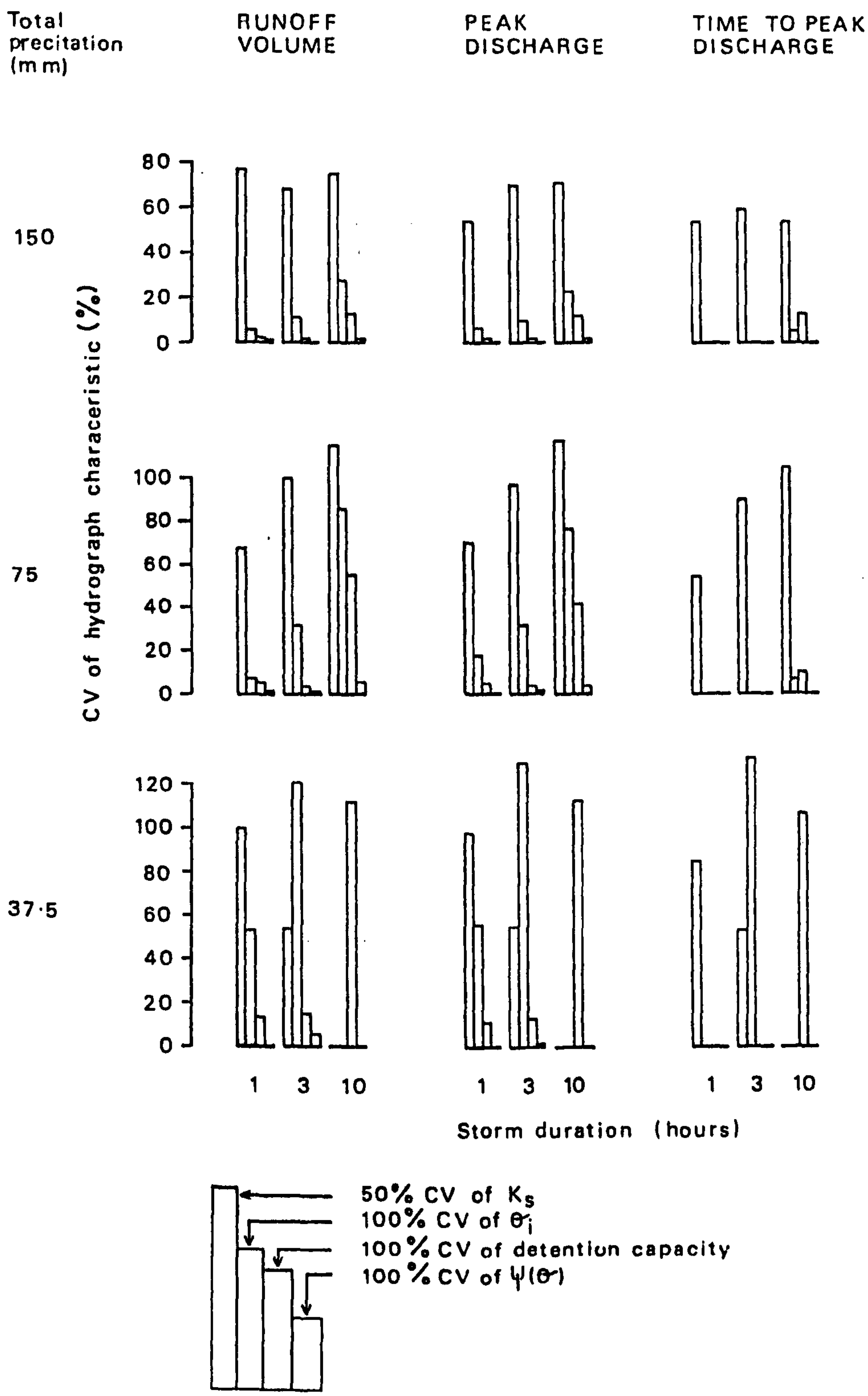


Figure 25: The relative sensitivity of HYMO2 to variation of four soil hydrological parameters, for nine storm conditions

lower than the magnitude of variation of detention capacity, except for the longer duration and very low intensity storms. Variation in input parameter variability tends to become dampened. This can be explained in terms of the checks which are made on the randomly generated value for detention capacity. As the coefficient of variation of the input parameter increases, there is a greater probability of the generated value being less than zero. Setting all such generated values to zero will decrease the variability.

Table 18 indicates that increasing the variability of the soil moisture characteristic curve from 6% to 100% produces very little change in the variation of runoff volume, peak discharge, or the time to peak. The model appears to be robust to errors of up to 100% in the specification of this soil hydrological parameter.

Secondly, for the applications of the stochastic sensitivity analysis, where all five parameters are varied simultaneously, the following comments can be made:

1 The relative sensitivity of the model to each of the parameters changes.

Table 19, which provides the information derived from simultaneous parameter variation deserves explanation. Firstly, to establish a control condition from which the relative sensitivity of each parameter can be established, the coefficient of variation of each of the 5 parameters has been kept very low, and the degree of flood hydrograph variation for each storm condition has been determined. The coefficient of variation of each parameter in turn was then increased to 100%, or 50% in the case of saturated hydraulic conductivity, whilst the variation of the others was held constant at the low level of the control condition.

The flood hydrograph over all nine storm conditions does remain most sensitive to saturated hydraulic conductivity, but the interactions

Table 19: Flood hydrograph sensitivity to simultaneous variation of all five soil hydrological parameters

Variation of input parameters	Total rain (mm)	CV of runoff volume (%)			CV peak discharge (%)			CV time to peak (%)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
Low variation in all parameters	150.0	3	7	15	3	6	11	0	0	5
	75.0	7	34	60	6	33	56	0	0	36
	37.5	16	113	-	17	126	-	0	69	-
50 % CV saturated hydraulic conduct- ity	150.0	35	29	64	35	29	60	33	8	56
	75.0	52	44	98	53	42	99	36	36	69
	37.5	57	182	-	58	189	-	54	71	-
100 % CV suction moisture curve	150.0	7	24	54	7	43	51	0	0	36
	75.0	16	92	183	16	90	178	0	55	86
	37.5	53	123	-	55	126	-	0	131	-
100 % CV initial moisture content	150.0	6	22	30	6	20	18	0	0	4
	75.0	14	36	200	15	36	208	0	7	162
	37.5	49	137	-	49	139	-	0	89	-
100 % CV saturated moisture content	150.0	3	6	27	3	27	19	0	0	3
	75.0	6	35	98	6	33	96	0	0	162
	37.5	17	126	-	18	125	-	0	69	-
100 % CV detention capacity	150.0	3	13	36	2	12	29	0	0	10
	75.0	5	38	81	6	36	78	0	7	33
	37.5	17	81	-	16	76	-	0	36	-

CV coefficient of variation - indicates no runoff between the parameters have the net effect of reducing the model's sensitivity to this parameter. The flood hydrograph is then most sensitive to error in the soil moisture characteristic curve, to initial soil moisture content, to saturated soil moisture content, and finally error in detention capacity produces the least variation. When saturated soil moisture content is varied alone, no variation in model output occured, but when all five parameters are varied, variation in this parameter will affect the range of possible soil moisture characteristic curves and also initial soil moisture conditions. When all five parameters are varied therefore, the model becomes relatively more sensitive to saturated soil moisture content than to detention capacity. The model appears to be more sensitive also to the soil moisture characteristic curve when all five parameters are varied simultaneously. It is relatively more sensitive to the soil moisture characteristic curve than to the initial soil moisture content.

These results have implications for the use of the infiltration model for the ungauged catchment. It will be necessary that the Brakensiek and Rawls method provides suitable values of saturated hydraulic conductivity and the soil moisture characteristic curve as these are the two parameters to which the model is most sensitive. However, the lower sensitivity to initial soil moisture content and detention capacity is encouraging for this application.

2 Variations of all input parameters causes a decrease in the predicted mean values of runoff volume, peak discharge, and time to peak.

Table 20 details firstly the mean values of the hydrograph produced where there is no variation of the five input parameters. It is then illustrated that a small amount of variation in each causes a reduction of between 5% in the case of high intensity, short duration storms, and 71% in the case of low intensity, longer duration storms, for both runoff volume and peak discharge. The predicted time to peak remains the same, except for lower intensity, longer duration storms, where small reductions in the order of 3% occur.

Table 20: Changes in the mean values of the hydrograph caused by simultaneous variation of all 5 soil hydrological properties

Variation of input parameters	Total rain (mm)	Mean runoff volume (mm)			Mean peak discharge (m^3s^{-1})			Mean time to peak (hours)		
		Storm duration (hours)								
		1	3	10	1	3	10	1	3	10
No variation in any parameter	150.0	142	137	91	177	159	62	3	4	9
	75.0	69	61	15	84	72	14	3	4	8
	37.5	30	24	-	37	28	-	3	4	-
Small variation in all parameters	150.0	135	124	61	167	142	48	3	4	9
	75.0	58	41	6	74	48	6	3	4	7.8
	37.5	23	8	-	27	8	-	3	3.2	-
50 % CV saturated hydraulic conductivity	150.0	124	124	71	155	143	50	2.7	4	2.7
	75.0	53	41	6	65	60	12	2.8	3.6	5.8
	37.5	23	6	-	27	6	-	2.4	2.1	-
100 % CV suction moisture curve	150.0	130	84	43	161	8	34	3	4	8
	75.0	53	30	2	66	35	2	3	3.3	5.1
	37.5	16	6	-	19	7	-	3	1.6	-
100 % CV initial moisture content	150.0	130	112	53	159	131	44	3	4	9.8
	75.0	53	48	3	66	56	2	3	4.1	2.6
	37.5	15	10	-	19	10	-	3	2.7	-
100 % CV saturated moisture content	150.0	135	122	66	167	156	51	3	4	9.9
	75.0	58	41	3	74	48	4	3	4	2.6
	37.5	22	7	-	27	8	-	3	3.2	-
100 % CV detention capacity	150.0	132	119	51	165	137	4	3	4	9.2
	75.0	58	41	11	71	48	9	3	4.1	8.8
	37.5	20	7	-	24	8	-	3	4.2	-

CV coefficient of variation - indicates no runoff

The variation of each parameter in turn was increased further to 100%, or 50% for saturated hydraulic conductivity, while the variation of the other four was held low. This indicates that the geatest reduction in mean predicted values occurs in response to variation of saturated hydraulic conductivity. A smaller reduction is caused by variation in the soil moisture characteristic curve, and variation of detention capacity and saturated soil moisture content does not cause any further reduction in runoff volume and peak discharge than the case where all five exhibit very low variation. Variation in these latter two variables however causes increases in predicted time to peak for some lower intensity, longer duration storms.

This section has illustrated that HYMO2 is sensitive to error in the five soil hydrological properties which are required by the infiltration model. This is encouraging as model parameters should be sufficiently sensitive to represent variation in infiltration and hence runoff which is associated with differences in soil properties in a catchment.

The model is most sensitive to saturated hydraulic conductivity, then to soil moisture characteristic curve and initial soil moisture content, particularly for long duration and low precipitation intensity events. These results indicate a realistic infiltration model. It is most sensitive to the most significant parameters in field conditions.

HYMO2 is considered to be a feasible alternative to the original model. It must be demonstrated however, that the Brakensiek and Rawls empirical method for deriving the values of these soil hydrological parameters is suitable. This will be investigated in chapter 5.

4.3 Examination of the accuracy of the explicit finite difference method

The third question pertinent to the computerized model verification concerns an assessment of the method of solution of the Richards equation.

Does the explicit finite difference method provide satisfactory results?

An initial examination has been undertaken of the numerical errors which are incurred in the solution of the Richards equation for the range of storm and catchment conditions which have been used in the sensitivity analysis. Further examination of these errors will continue with application of the model to actual catchment situations, where more complex soil columns (layered) and variable intensity precipitation will be experienced.

These numerical errors are measured by a cumulative mass water balance calculation (equation 48). Table 21 illustrates that for the nine storm conditions used in the stochastic sensitivity analysis and for those conditions where there is no input parameter variation, negligible errors are incurred.

This initial examination, for a range of simple conditions, indicates that the explicit finite difference method does appear to be a suitable numerical method for the solution of the one dimensional Richards equation which is used in this particular application. Negligible errors are experienced.

It must be stressed at this point that despite the thorough and, it would be argued here, successful computer model verification of HYMO2 which has been undertaken and reported in this chapter, emphasis must be placed upon the following two points. Firstly, it is highly improbable that all software errors will have been discovered and remedied. The presence of errors in this computer program, as indeed in all software currently available, should be an expectation of the user. The model predictions which are provided should not be accepted blindly or uncritically. However, the improbability of providing a completely error free computer program should not provide an excuse for the model builder for not attempting to verify the code. Secondly, many software errors which do occur are most commonly a function of the manner in which the program is used rather than an inherent property of the

Table 21: Numerical error (BAL) derived for the nine simple storm conditions indicated in figure 24

Total rain (mm)	BAL* (m^3m^{-3}) Storm duration (hours) 1	3	10
150.0	$0.1x10^{-4}$	$0.15x10^{-4}$	$0.15x10^{-4}$
175.0	$0.3x10^{-4}$	$0.3x10^{-4}$	$0.4x10^{-4}$
37.5	$0.3x10^{-4}$	$0.5x10^{-4}$	$0.3x10^{-4}$

* BAL is defined in equation (48) in the text

program. Many users will take little time fully to appreciate the specification of the model which is provided. They will consequently apply the program outside its design limits. The errors which will occur can not therefore be attributed to programming errors. However, those users who do fully acquaint themselves with the model specification may be unfortunate enough to have been provided with a specification which is inaccurate or insufficiently detailed. Once again, the emphasis is placed upon the model developer to provide an appropriate model specification.

The third stage of model evaluation, operational validation, will be examined in the following chapter.

5

Model evaluation III: Operational validation of HYMO2

Operational validation is the third stage of model evaluation, and aims to establish a measure of the extent to which the model, the program implementing it, and the empirical methods used to provide parameter estimates, represent an accurate representation of reality. This evaluation is necessary since the status, and usefulness, of HYMO2 depend upon the range of conditions under which it holds.

This validation is implemented by a comparison of predicted and observed hydrographs for a wide range of catchment and storm conditions. There will nearly always be some flood event and basin conditions where the model produces satisfactory results. Dawdy and Thompson (1967), Garrick et al (1978) and Naef (1981) all stressed that as the rainfall, runoff process is good natured and stable, then even a simple model can provide good predictions in some circumstances. If a model is to be considered useful, prediction error must be small for a wide range of applications.

In any analysis, it is impossible to investigate the behaviour of the model for all possible conditions. Assessments of the useful application of the model must therefore be made from a limited number of experimental frames. In this chapter, discharge and precipitation data for the North Creek catchment, Texas, and the Sixmile Creek, Arkansas, United States of America will be used to begin to explore the operational validity of HYMO2, incorporating the infiltration model. It must be stressed however, that operational validation will proceed with further applications of the newly configured model which will be documented in chapter 6. However, figure 26 indicates the locations of

Figure 26: Location of the North Creek, Texas and the Sixmile Creek, Arkansas

the two catchments which are to be used in this chapter, and figures 27 and 28 supply detail of the soil and relief characteristics of each catchment. The characteristics of the unit hydrograph derived for both catchments from the dimensionless unit hydrograph method in HYMO2 are illustrated in figure 29 and table 22. Information concerning the storms which were applied to the catchments is provided by table 23. For convenience, throughout this thesis, each experimental frame will be referred to by catchment name and the storm number indicated in table 23, rather than by the date. The nearest recording raingauge is located 11.26 km from the North Creek, and 9.65 km from the Sixmile Creek catchment.

The performance, or reliability, of any model has two dimensions. In practical application there is interest in the reliability of predictions, and in scientific applications emphasis is placed upon reliability in the replication of the prototype system and to contributions which the model makes to hydrological understanding. It should be stressed that interest in this operational validation is focused firmly upon the former aspect of reliability, the replication of the actual catchment discharge hydrograph.

In order to address those questions which were raised in section 2.5, concerning the operational validity of the modified model, this chapter will be divided into three sections: an examination of parameter estimation for the infiltration model, a comparison of a series of calculated and measured hydrographs, and an application of the stochastic version of HYMO2.

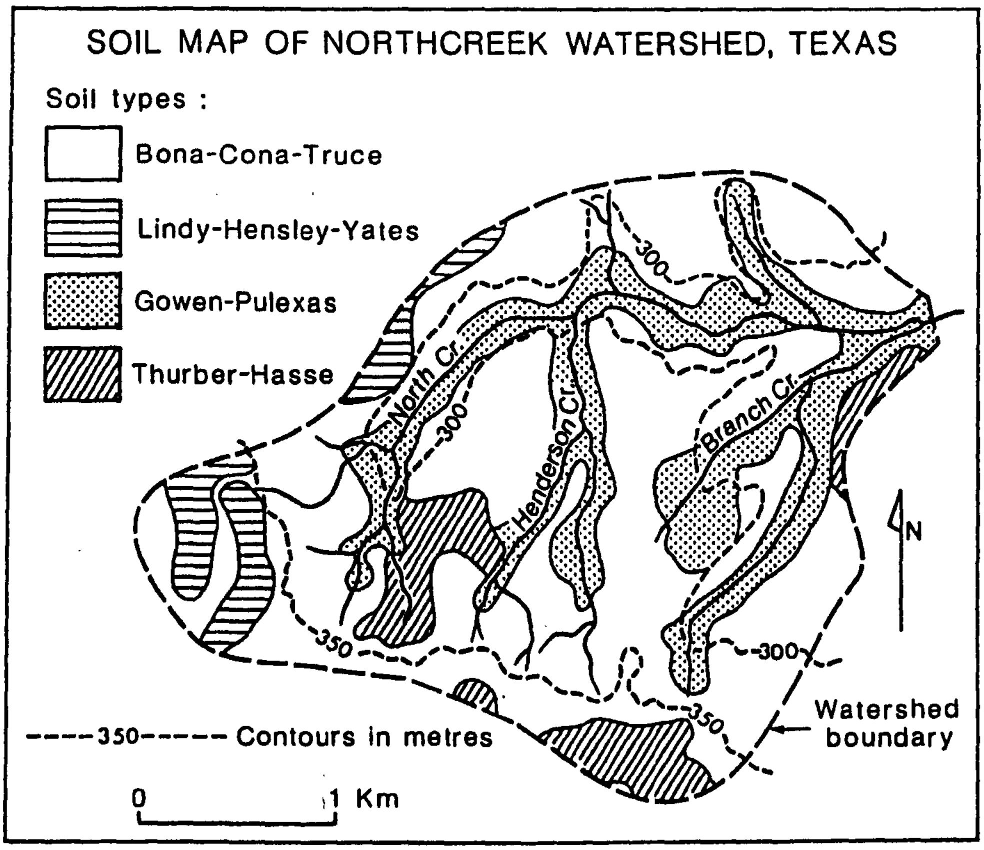


Figure 27: North Creek catchment, Texas

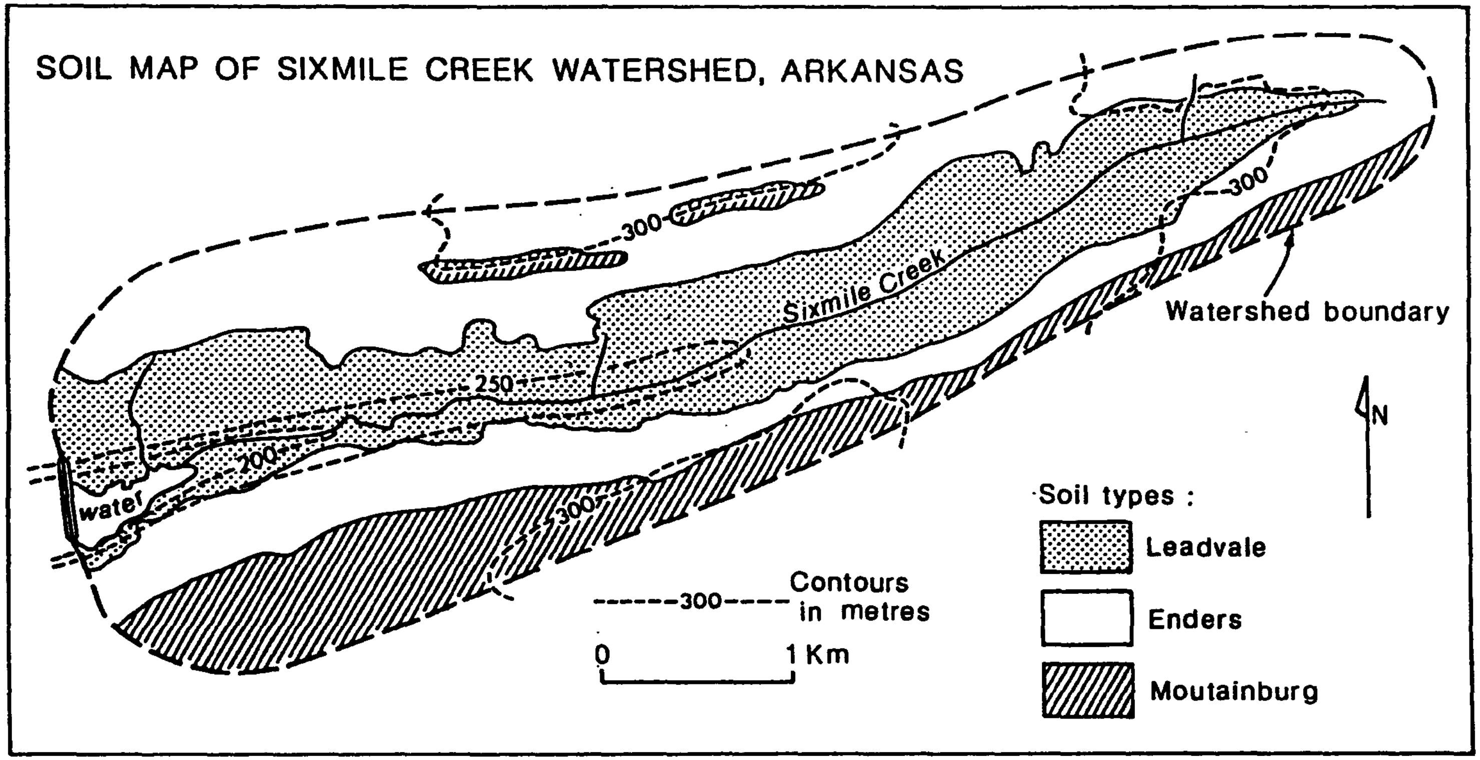


Figure 28   Sixmile Creek catchment, Arkansas

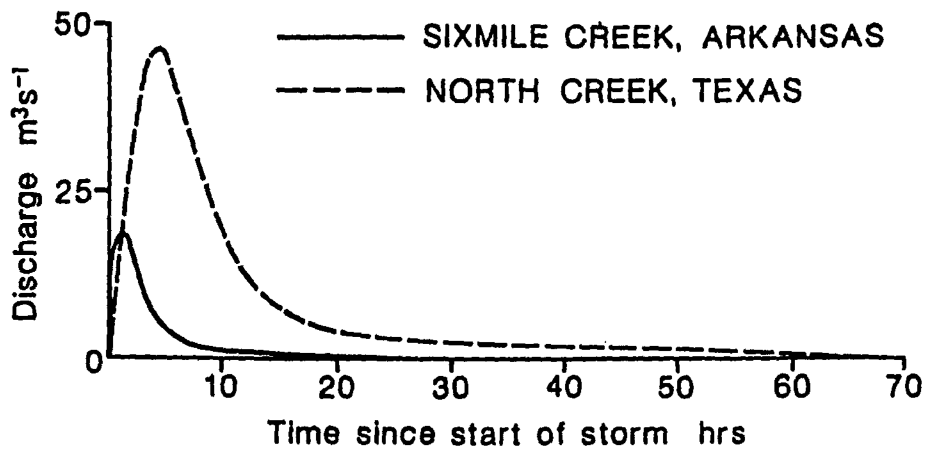


Figure 29: Unit hydrographs for North Creek and Sixmile Creek

Table 22: Comparison of catchment characteristics

	Area (km^2)	Elevation difference (metres)	Length main channel (km)	Unit peak (m^3s^{-1})
North Creek	61.6	108.0	5.3	44.4
Sixmile Creek	11.0	79.0	8.3	18.0

Table 23: Characteristics of storms applied to North Creek, Texas and Sixmile Creek, Arkansas

	Date (d.m.yr)	Time of storm start (hrs)	Time increment rain data (hrs)	Storm duration (hrs)	Total rain (mm)
	North Creek, Texas				
1	9.10.1962	21.5	0.25	8.25	74.5
2	27.7.1962	2.0	0.25	9.0	76.7
3	18.9.1965	18.7	0.1	1.3	107.2
4	22.4.1966	8.0	0.5	7.5	86.1
5	4.5.1969	21.5	0.25	7.5	69.8
6	6.5.1969	15.25	0.25	8.75	45.2
	Sixmile Creek, Arkansas				
1	20.3.1955	10.0	0.25	8.0	69.6
2	17.11.1957	18.0	0.25	16.0	73.7
3	25.6.1958	8.0	0.25	14.0	108.5
4	3.11.1959	18.5	0.5	8.5	101.6
5	10.12.1960	6.0	0.25	17.0	72.6
6	4.5.1961	4.0	0.25	6.0	85.6

5.1 Examination of the utility of the Brakensiek and Rawls empirical information and the implications of the choice of iteration period for solution of the infiltration equation.

Is the Brakensiek and Rawls empirical information for deriving soil hydrological parameters suitable for the application of HYMO2? What is the effect of the choice of iteration period, for the solution of the infiltration equation, upon predictions provided by HYMO2?

These two questions will be examined with reference to application of HYMO2 to the North Creek and the Sixmile Creek.

North Creek, Texas

The soils of the North Creek catchment are represented by three soil columns. The map of the catchment (figure 27) indicates that there are four soil types. However, the Lindy-Hensley-Yate group is omitted for two reasons. Firstly, a soil column representing the soil type did not produce any runoff for any of the storms applied to the catchment, and secondly, it occupies only 4% of the total catchment area.

The various experimental frames which have been used to examine these two questions will now be outlined. Information concerning the landuse, soil texture, and depth of layers within the three soil columns which represent the Bona-Cona-Truce, Gowen-Pulexas, and Thurber-Hasse soils of the North Creek, were derived entirely from the soils map and accompanying description. This information is provided in tables 24, 25, and 26, and figure 30.

The hydrological characteristics of each soil column, and for each layer were estimated from the information in figures 17 and 18, compiled from Brakensiek and Rawls (1983). The exact percentage clay and percentage sand information is not available and therefore, an estimate must be made of the position of each soil texture group on the charts to enable

Table 24: Soils information for Bona-Cona-Truce, North Creek, Texas

		Bona-Cona-Truce		
		Layer 1	Layer 2	Layer 3
Depth (metres)		0.15	0.46	0.31
Soil texture		sandy loam	clay	clay
Saturated soil moisture content ($m^3 m^{-3}$)		0.4	0.48	0.48
Initial relative saturation		>0.95	>0.95	>0.95
Suction moisture curve		See figure 30		
Saturated hydraulic conductivity ($m^3 s^{-1}$)	i	9.7×10^{-6}	2.1×10^{-8}	2.1×10^{-8}
	ii	2.8×10^{-5}	2.8×10^{-7}	2.8×10^{-7}
Landuse		Rangeland		
Detention capacity (metres)		0.0		
% total basin area		67%		

i - values derived from centroid position
ii - values derived from highest percentage clay

Table 25: Soils information for Gowen-Pulexas, North Creek, Texas

		Gowen-Pulexas		
		Layer 1	Layer 2	Layer 3
Depth (metres)		0.61	0.3	0.61
Soil texture		loam	clay loam	sandy clay loam
Saturated soil moisture content ($m^3 m^{-3}$)		0.4	0.36	0.32
Initial relative saturation		>0.95	>0.95	>0.95
Suction moisture curve			See figure 30	
Saturated hydraulic conductivity ($m^3 s^{-1}$)	i ii	2.4×10^{-6} 5.6×10^{-6}	4.2×10^{-7} 1.1×10^{-6}	3.9×10^{-6} 2.8×10^{-5}
Landuse			Rangeland	
Detention capacity (metres)			0.0	
% total basin area			23%	

i - values derived from centroid position
ii - values derived from highest percentage clay

Table 26: Soils information for Thurber-Hasse, North Creek, Texas

	Thurber-Hasse		
	Layer 1	Layer 2	Layer 3
Depth (metres)	0.15	0.61	0.61
Soil texture	clay loam	clay	clay
Saturated soil moisture content ($m^3 m^{-3}$)	0.36	0.48	0.43
Initial relative saturation	>0.95	>0.95	>0.95
Suction moisture curve	See figure 30		
Saturated hydraulic conductivity ($m^3 s^{-1}$) i ii	4.2×10^{-7} 1.1×10^{-6}	2.1×10^{-8} 2.8×10^{-7}	2.1×10^{-8} 2.8×10^{-7}
Landuse	Rangeland		
Detention capacity (metres)	0.0		
% total basin area	15%		

i - values derived from centroid position
ii - values derived from highest percentage clay

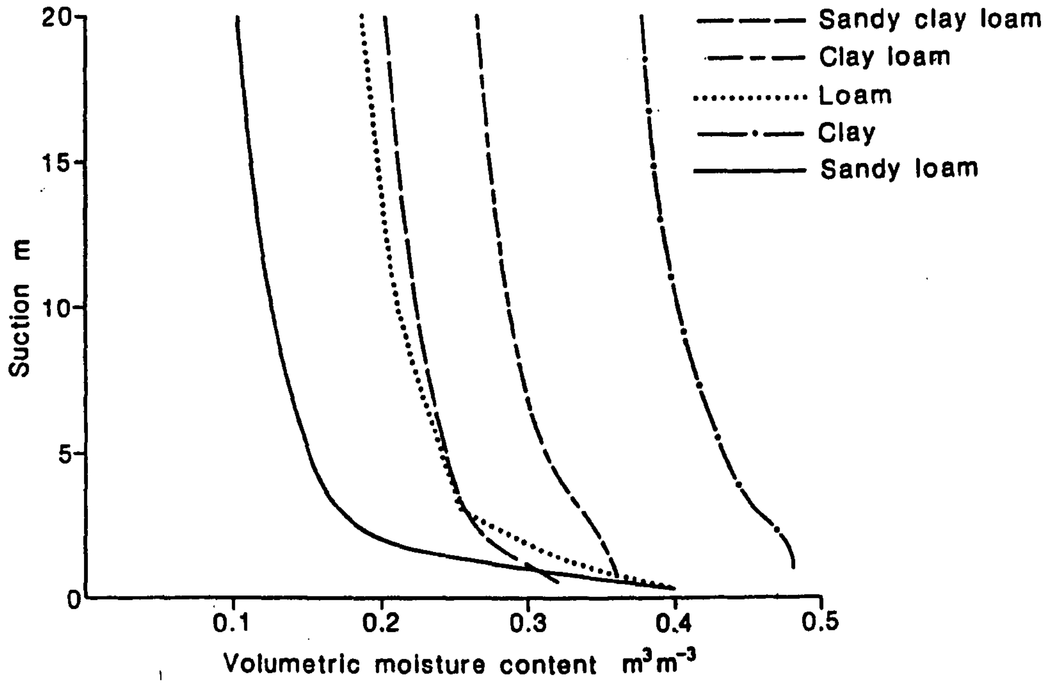


Figure 30: Soil moisture characteristic curves for soils in the North Creek, derived from figure 17

the soil moisture characteristic curve, saturated soil moisture content, and saturated hydraulic conductivity to be determined. It follows therefore, that the sensitivity of the model to the position (percentage clay and percentage sand) which is chosen should be established. In order to investigate this question, it is necessary to establish the soil hydrological properties which correspond to a variety of positions within each soil texture group, and to determine the model's sensitivity to these positions. It has been shown in chapter 4 that the model is most sensitive to saturated hydraulic conductivity and hence, this is the most important controlling parameter on the response of infiltration to precipitation, and therefore, the position of this parameter only was varied.

The soil moisture characteristic curve and saturated soil moisture content values which corresponded to the centroid position of each soil texture group were used for all applications considered here. Two values for saturated hydraulic conductivity were determined, one corresponds to the centroid position (i in tables 24, 25, and 26) and the other to the highest percentage clay in each soil texture group (ii in tables 24, 25, and 26). For all soil texture groups, the organic matter content was assumed to be 0.5%.

The initial relative saturation of the soil could be estimated from the rainfall information of the 5 day period previous to each storm which is available for this catchment. For most of the storms applied to the catchment however, a very high initial relative saturation is required to generate sufficient runoff. For the same reason, detention capacity is assumed to be zero.

From this information, three different data sets were determined, which vary only in terms of the values of saturated hydraulic conductivity. These were used for application of the 6 storms (table 23) to the North Creek. These three data sets comprise:

A Saturated hydraulic conductivity values for the soil textures of all three layers in each soil column. These were derived from the highest clay percentage on the Brakensiek and Rawls charts.

B Saturated hydraulic conductivity values for all soil textures. These were derived from the centroid position on the Brakensiek and Rawls charts.

C A combination of the saturated hydraulic conductivity values generated from the highest percentage clay for the soil column, which represents the Gowen-Pulexas occupying the flood plain area, with that generated from the centroid positions for the other two soil types.

To establish whether or not the choice of iteration period has an effect upon the model predictions, two iteration periods, 60 and 10 seconds are considered. Each of the three data sets A, B and C which have now been described were run with a 60 and 10 second iteration period. In total therefore, six data sets have been established. The consequences of the use of the Brakensiek and Rawls method and choice of iteration period upon predictions provided by the modified HYMO to six storms applied to the North Creek catchment will now be examined.

Figures 31, 32, and 33 detail the effects of the six data sets upon runoff, peak discharge, and time to peak discharge respectively. Each figure provides, for all storms, a comparison of the measured value to those provided by the six data sets. In total, 34 experimental frames are provided. Figure 34 illustrates the variation of the error standard deviation (equation 29), which provides a measure of the overall goodness of fit of the calculated and measured hydrographs. For storm 3, the predictions provided by the data set C, the combination of saturated hydraulic conductivity values, at 10 and 60 seconds iteration periods are not provided as they were very much higher than the measured.

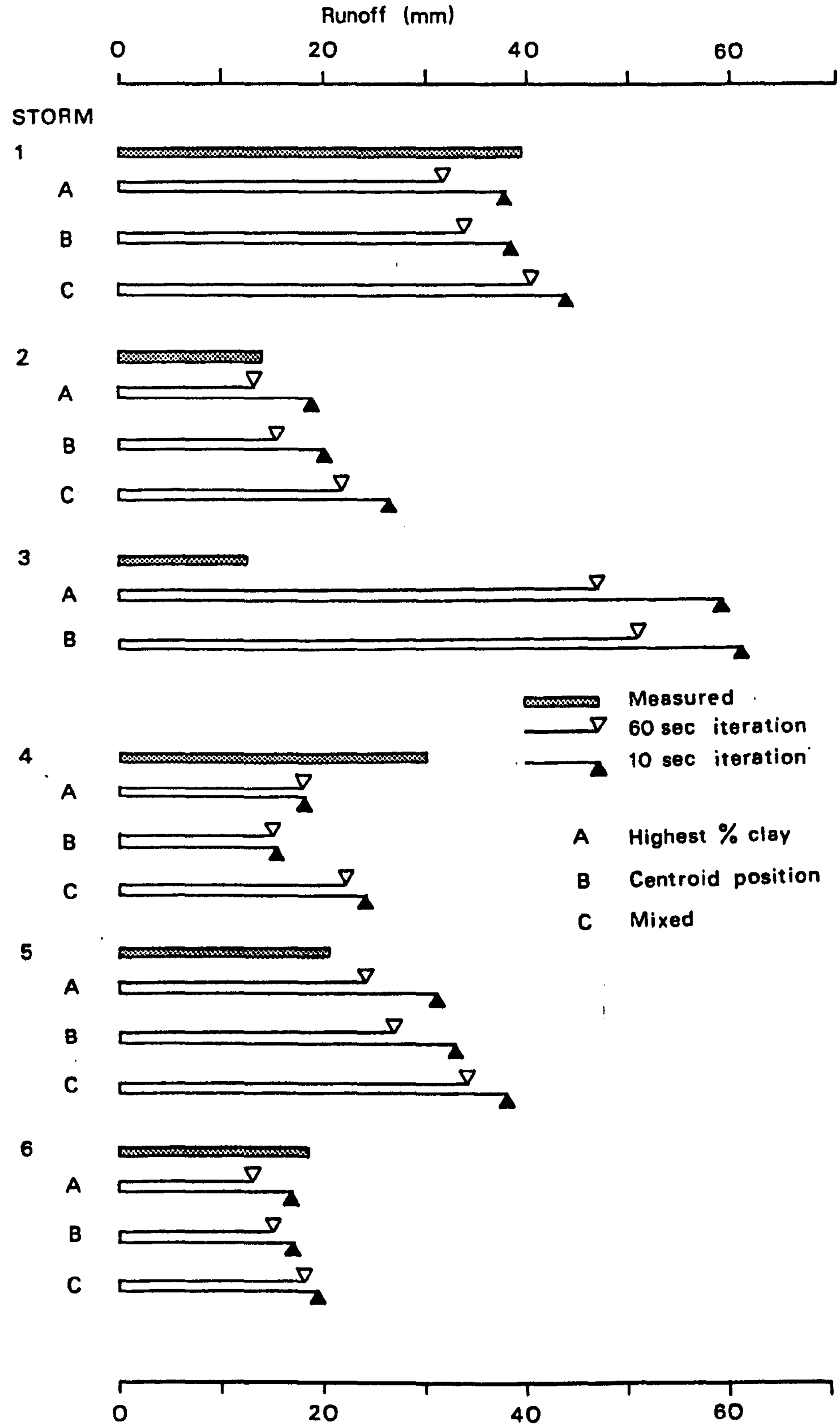


Figure 31: Runoff predictions for a range of soils data and iteration periods for 6 storms, North Creek

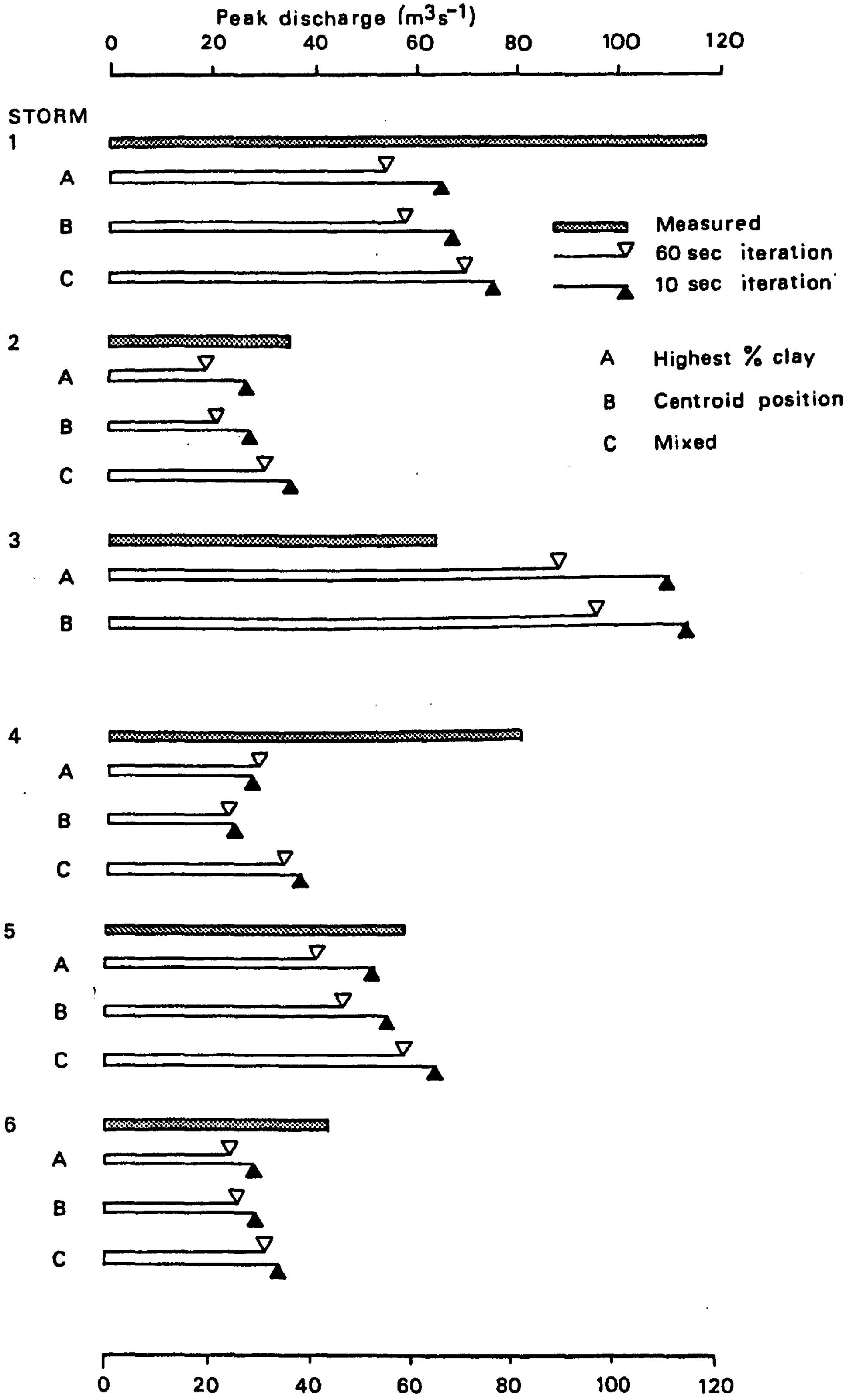


Figure 32: Peak discharge predictions for a range of soils data and iteration periods for 6 storms, North Creek

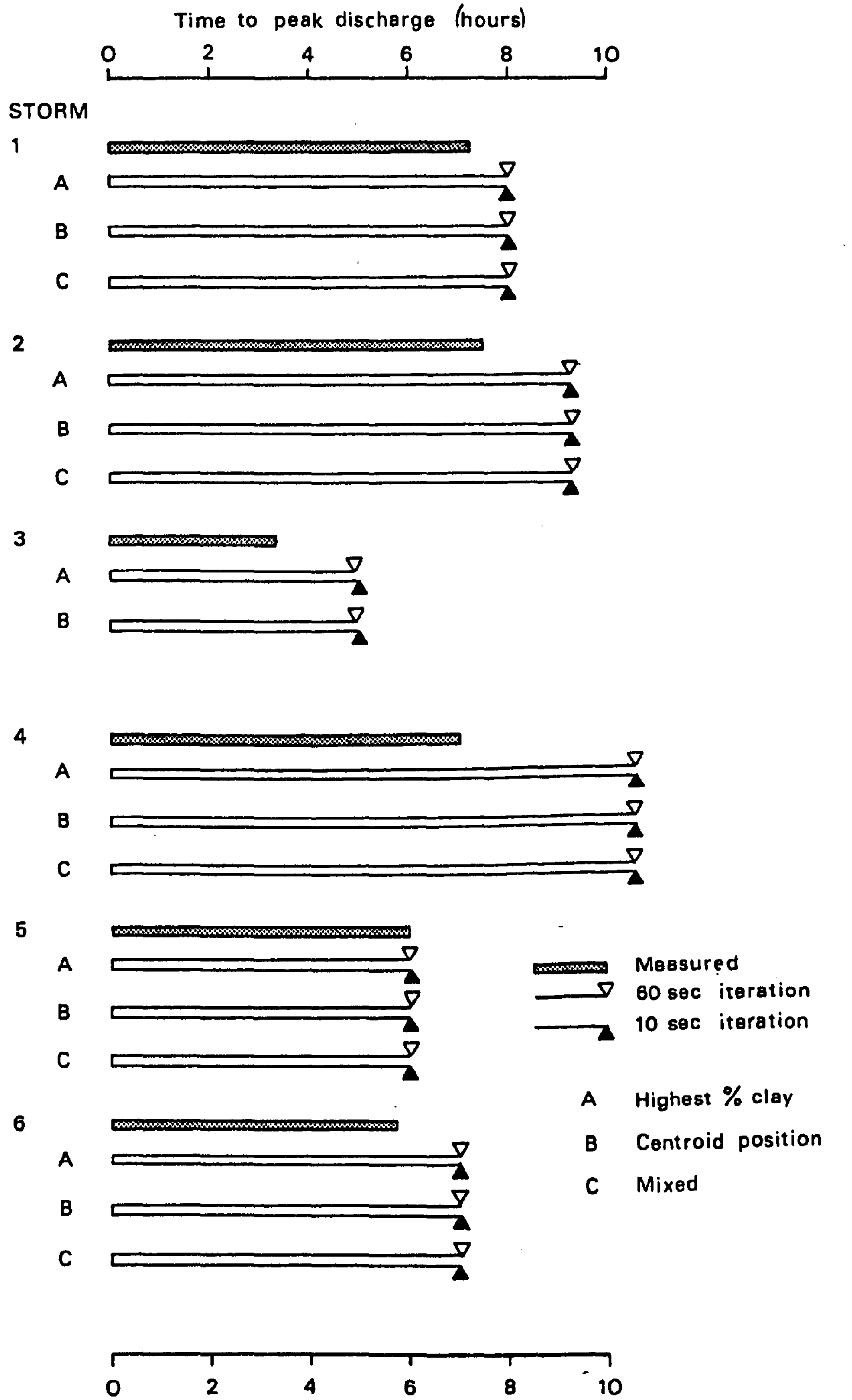


Figure 33: Time to peak discharge predictions for a range of soils data and iteration periods for 6 storms, North Creek

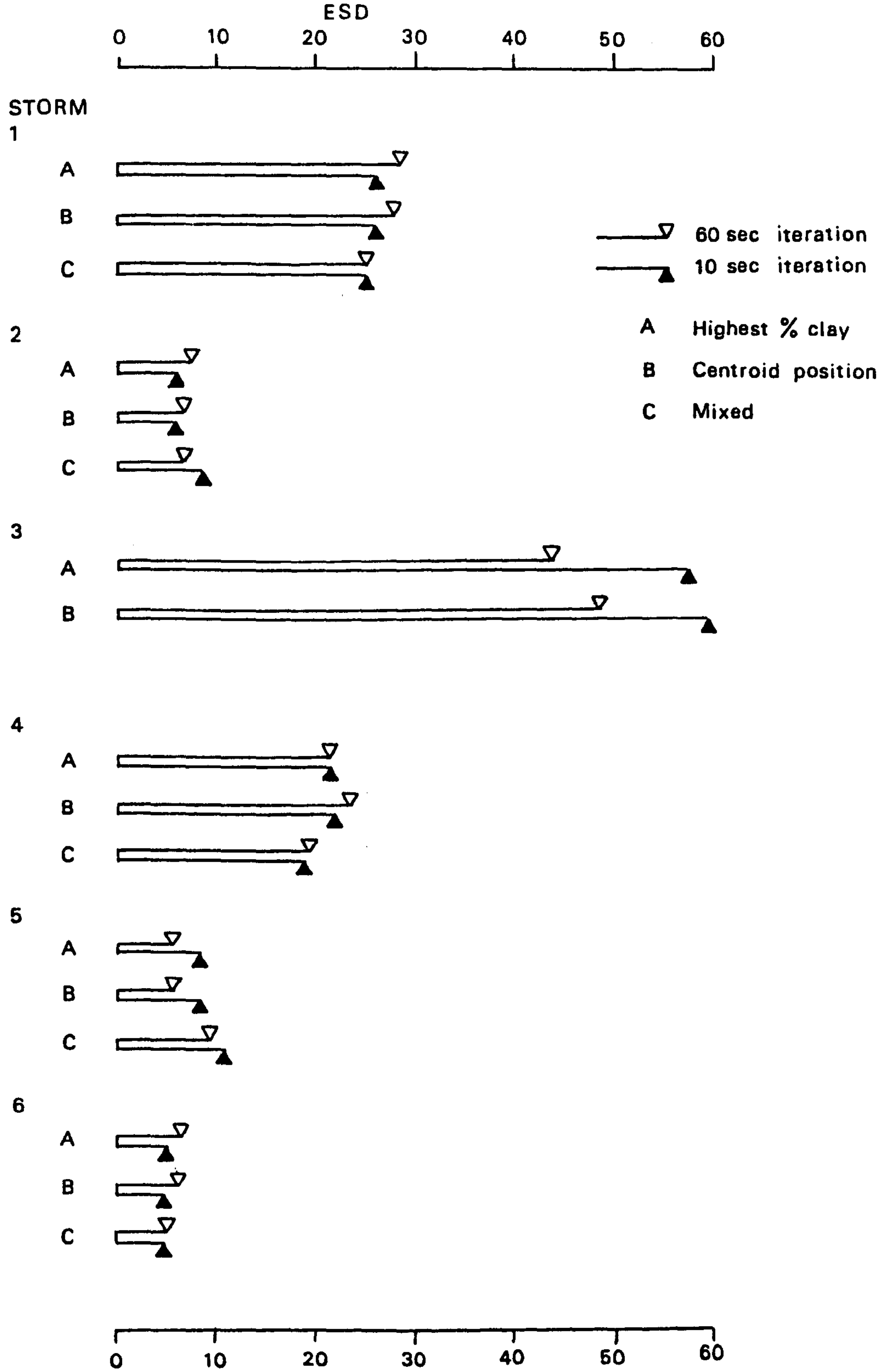


Figure 34: Error standard deviation (ESD) for a range of soils data and iteration periods for 6 storms, North Creek

From figures 31 to 34, the following points can be made:

1 HYMO2, which uses soils data derived from the Brakensiek and Rawls information, provides very reasonable predictions of runoff (except for storm 3) and very good predictions of time to peak (except for storm 4). However, it considerably underestimates peak discharge (with the exception of storm 3). Storm 3 is characterized by the highest intensity and shortest duration of the 6 storms.

2 Calculated runoff and peak discharge are sensitive to the choice of the position of the soil on the soil textural diagram. For all storms, the greatest runoff, and hence the greatest peak discharge, is provided by the soil data set C, which implicitly considers the location of the soil type on the catchment. Time to peak is not sensitive to the choice of soils data.

3 Calculated runoff and peak discharge are sensitive to the choice of iteration period. Use of 10, rather than 60 seconds can produce more runoff. When a 60 second iteration period is used, more error in the solution of the Richards equation results, and this is manifest in a loss of water content in the soil which consequently reduces runoff. Only a very slight sensitivity of time to peak to the iteration period is displayed for storm 3.

4 The best estimate of runoff for each storm is not produced by the same combination of soils data and iteration period. However, the best estimates of peak discharge for storms 1, 2, 4, and 6 are provided by the same data set, soils data C at 10 seconds.

5 The error standard deviation indicates that the hydrographs predicted by storms 2, 5, and 6 for all six data sets appear to be good. A smaller sensitivity to the soils data sets and iteration period is displayed by this measure of the overall fit of the calculated to the measured hydrograph. Figure 35 illustrates the range of hydrographs produced by the six data sets for storm 4. Their overall form is very similar and they differ only in the peak discharge.

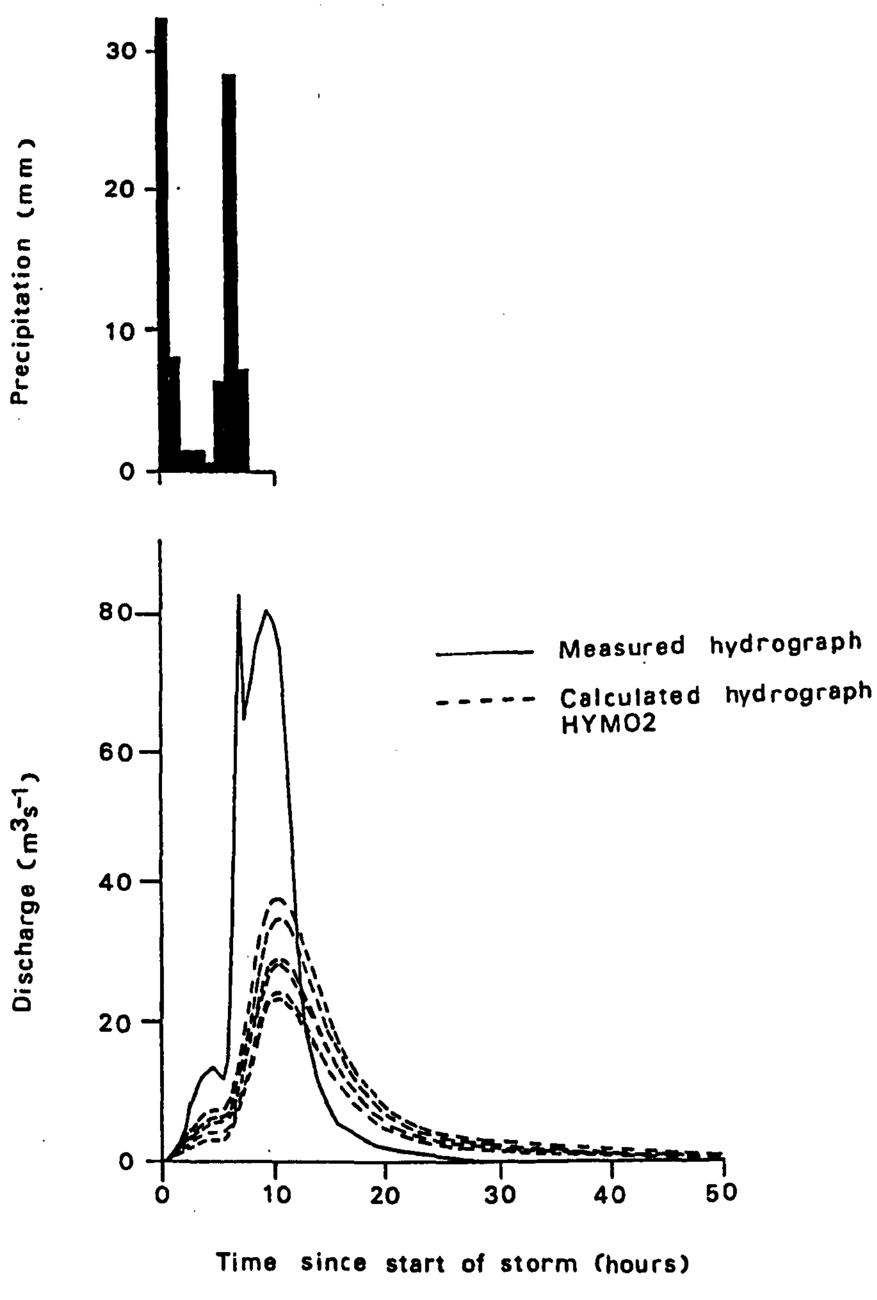


Figure 35: The measured hydrograph compared to the range predicted by HYMO2 for a range of soils data and iteration periods for storm 4, 22 April 1966, North Creek

Sixmile Creek, Arkansas

The soils of the Sixmile Creek: Leadvale, Enders, and Mountainburg, are also represented by three soil columns. All of the necessary information was derived entirely from the soils and topography map, and the charts developed by Brakensiek and Rawls (figures 17 and 18). For this catchment, the exact percentage clay and percentage sand data are available for each soil texture group. Use of these values however, for the derivation of the soil hydrological data, and application to the catchment, produced no runoff for any of the storms. Those values corresponding to the highest percentage clay for each soil texture group were therefore used and an organic matter content of 0.5% was assumed. As for the application to the North Creek, initial relative saturation was set at a high value, and detention capacity was set to zero. This soils information is given in tables 27, 28, 29, and figure 36.

For application to the Sixmile Creek, two data sets were derived:

- A The soil hydrological data corresponding to the highest percentage clay for the soil texture group of each layer.

- B The actual percentage clay and percentage sand information which is available for this catchment.

Each of these were used with a 10 and 60 second iteration period. In total therefore, four data sets have been established. The consequences of these data sets upon the predictions calculated for 6 storms applied to the Sixmile Creek are provided in figures 37, 38, 39, and 40. In total, 24 experimental frames are provided in these figures from which the following points can be made.

1 In comparison to the measured hydrographs, the predictions provided for the Sixmile Creek are much better overall, than those predicted for the North Creek catchment.

Table 27: Soils information for Leadvale, Sixmile Creek, Arkansas

	Leadvale		
	Layer 1	Layer 2	Layer 3
Depth (metres)	0.15	0.46	0.76
Soil texture	silt loam	silt clay loam	silty clay
Saturated soil moisture content (m^3m^{-3})	0.49	0.52	0.53
Initial relative saturation	>0.95	>0.95	>0.95
Suction moisture curve	See figure 36		
Saturated hydraulic conductivity (m^3s^{-1})	$8.3x10^{-6}$	$6.9x10^{-7}$	$1.4x10^{-7}$
Landuse	Rangeland		
Detention capacity (metres)	0.0		
% total basin area	47%		

Table 28: Soils information for Enders, Sixmile Creek, Arkansas

	Enders		
	Layer 1	Layer 2	Layer 3
Depth (metres)	0.18	0.69	0.18
Soil texture	silt loam	clay	clay
Saturated soil moisture content ($m^3 m^{-3}$)	0.49	0.52	0.52
Initial relative saturation	>0.95	>0.95	>0.95
Suction moisture curve	See figure 36		
Saturated hydraulic conductivity ($m^3 s^{-1}$)	8.3×10^{-6}	2.8×10^{-7}	2.8×10^{-7}
Landuse	Rangeland		
Detention capacity (metres)	0.0		
% total basin area	28%		

Table 29: Soils information for Mountainburg, Sixmile Creek, Arkansas

	Mountainburg		
	Layer 1	Layer 2	Layer 3
Depth (metres)	0.8	0.3	0.1
Soil texture	sandy loam	sandy clay loam	sandy clay loam
Saturated soil moisture content ($m^3 m^{-3}$)	0.41	0.41	0.41
Initial relative saturation	>0.95	>0.95	>0.95
Suction moisture curve		See figure 36	
Saturated hydraulic conductivity ($m^3 s^{-1}$)	2.8×10^{-5}	2.8×10^{-5}	2.8×10^{-5}
Landuse		Rangeland	
Detention capacity (metres)		0.0	
% total basin area		25%	

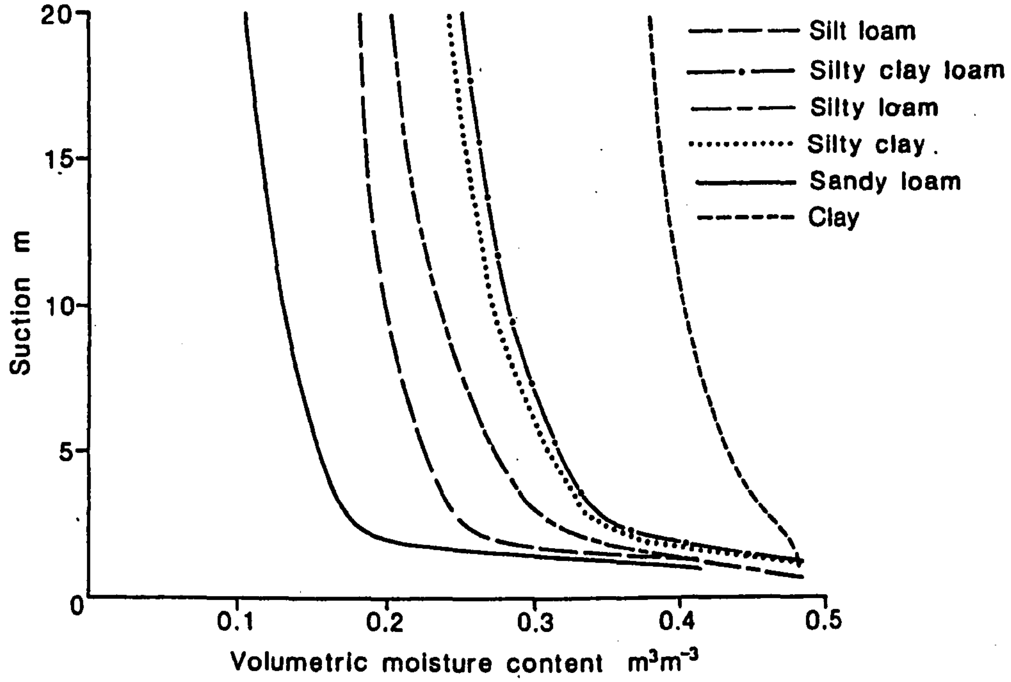


Figure 36: Soil moisture characteristic curves for soils in the Sixmile Creek, derived from figure 17

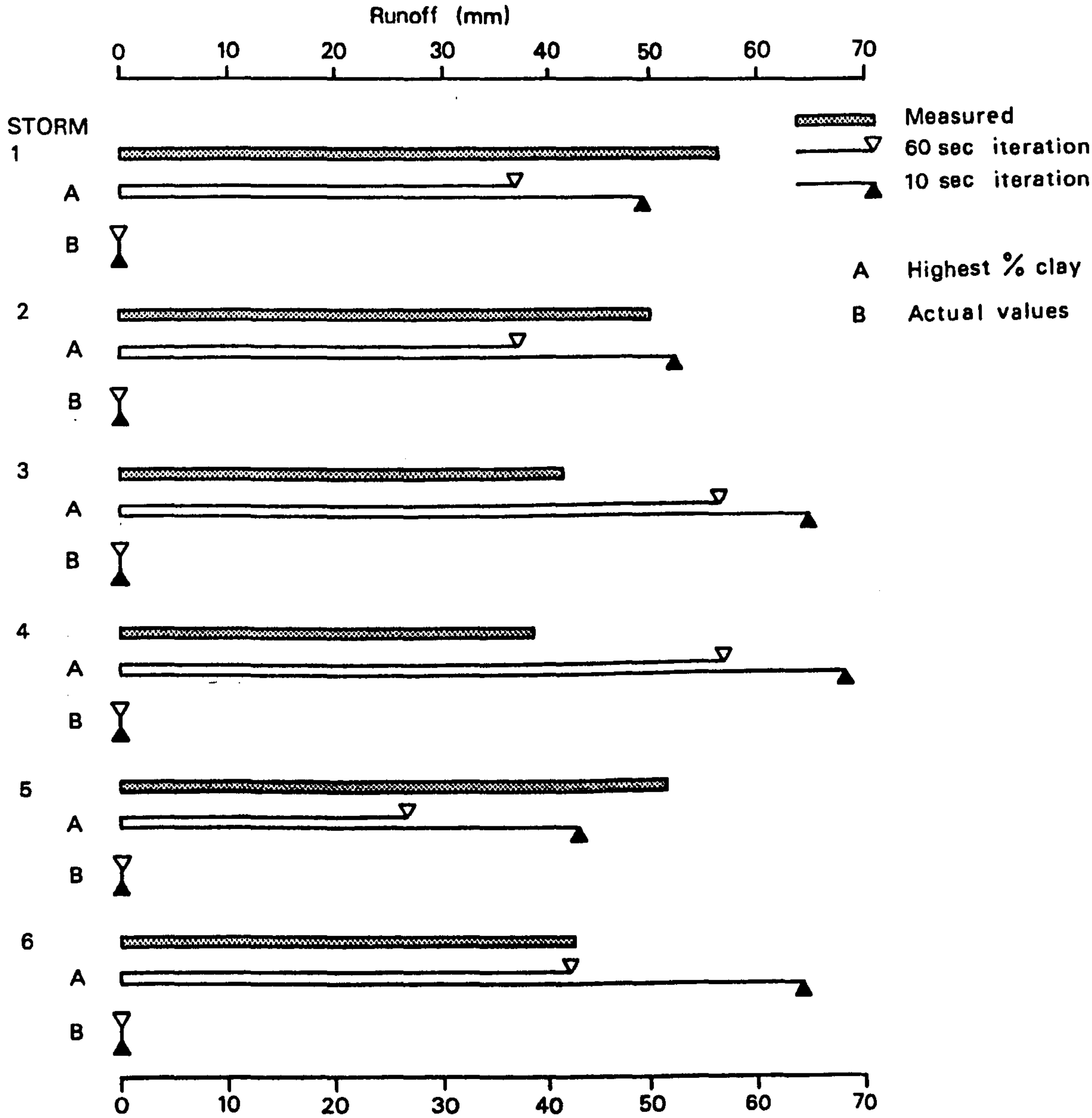


Figure 37: **Runoff predictions for a range of soils data and iteration periods for 6 storms, Sixmile Creek**

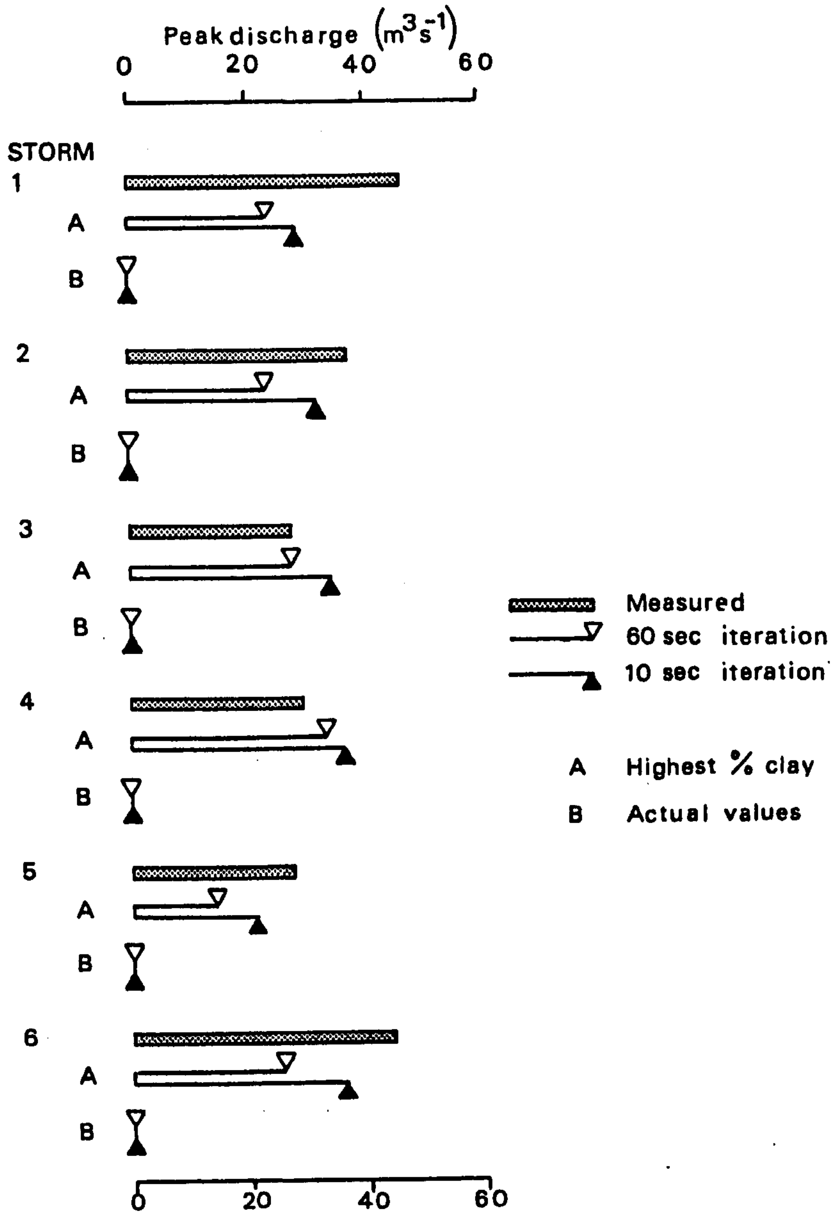


Figure 38: Peak discharge predictions for a range of soils data and iteration periods for 6 storms, Sixmile Creek

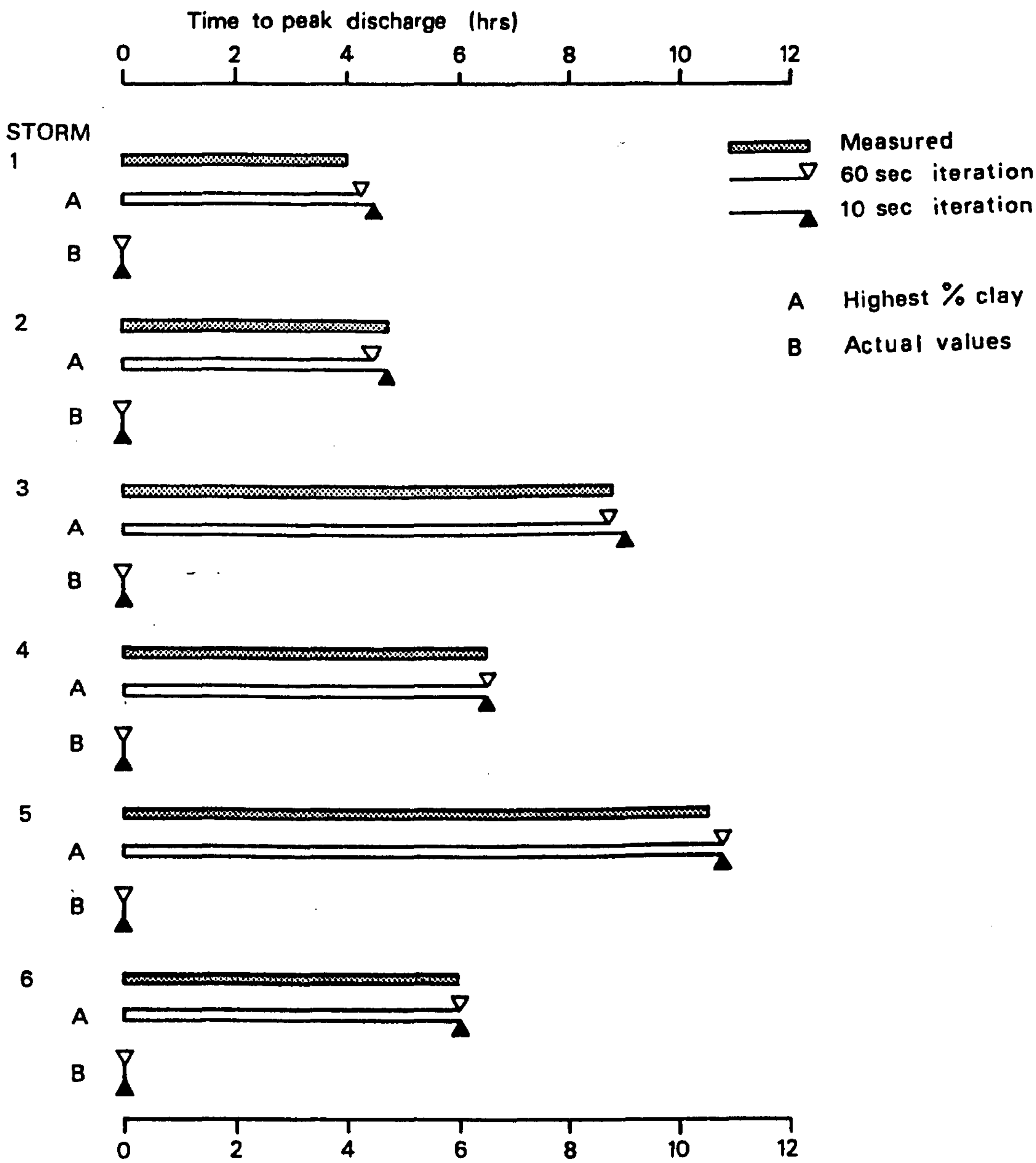


Figure 39: Time to peak discharge predictions for a range of soils data and iteration periods for 6 storms, Sixmile Creek

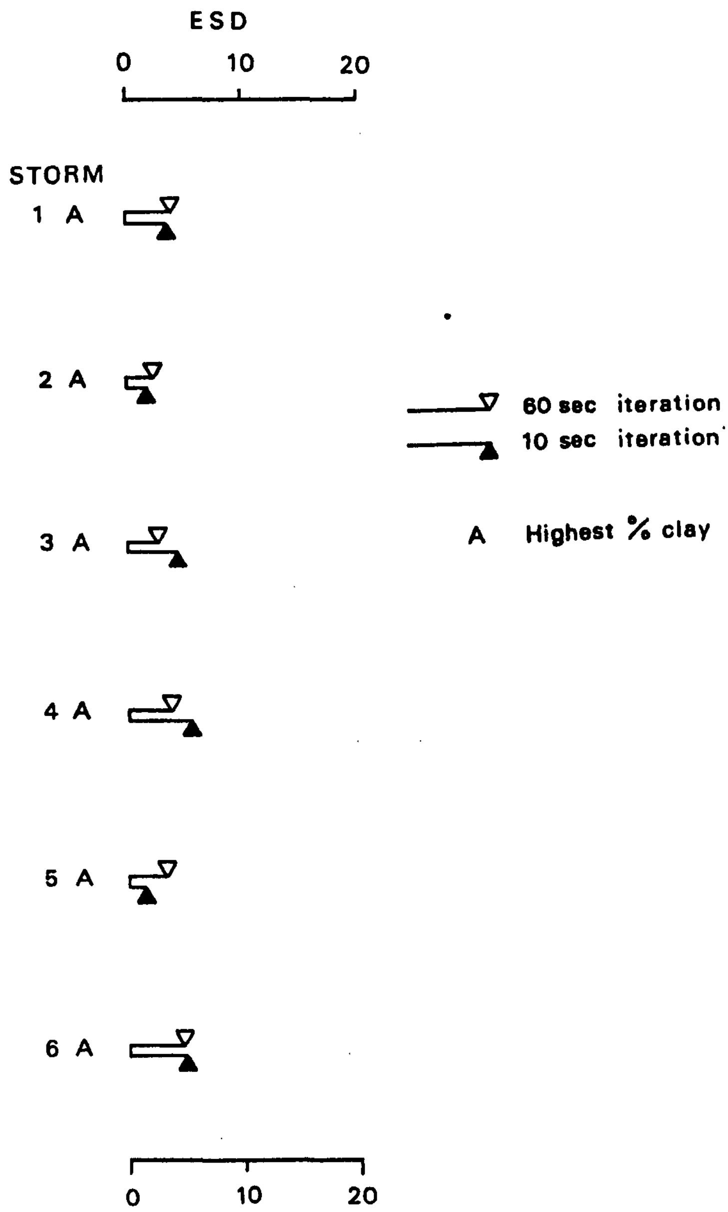


Figure 40: Error standard deviation (ESD) for a range of soils data and iteration periods for 6 storms, Sixmile Creek

2 Quite reasonable approximations to the measured runoff values and very good predictions of peak discharge and time to peak are derived for all storms where the soils information corresponding to the highest percentage clay for each soil texture group is used.

3 Calculated runoff and peak discharge are very sensitive to the choice of soils information.

4 Calculated runoff and peak discharge are sensitive to iteration period. Increases in runoff of up to 52% can be derived by reducing the iteration period from 60 to 10 seconds. Time to peak discharge is only very slightly sensitive to iteration period.

5 The best estimates of runoff, peak discharge, and time to peak for each storm are not produced by the same iteration period.

6 Over the range of storms, the error standard deviations (figure 40) illustrates that the calculated hydrograph derived for the highest percentage clay soils data very closely fits the measured hydrograph. The maximum error standard deviation is 5.4. This index is sensitive to the choice of soils data but not to the iteration period.

From the evidence based on 58 experimental frames which have now been discussed, and which involved applications to two diverse catchments, the following comments can be made. The Brakensiek and Rawls method is a suitable empirical procedure for deriving soils information for the infiltration component of the modified HYMO for an ungauged catchment. The 58 experimental frames do illustrate that the model predictions of runoff and peak discharge are sensitive to the percentage clay and percentage sand which are selected, but that time to peak and the overall closeness of fit of the calculated hydrograph are not. The iteration period which is chosen also affects model predictions. Smaller time increments do allow more accurate solutions to be made.

5.2 Comparison of calculated and measured hydrographs

How well does HYMO2 predict the discharge hydrograph of a storm event?

Operational validation involves a comparison of calculated and measured hydrographs. It is necessary to offer a quantitative assessment of the goodness of fit of the calculated to the measured discharge. This is achieved by the application of various graphical and numerical comparisons. Section 2.1.2 describes two numerical indices (the error standard deviation and the peak discharge error) which the original HYMO configuration offers. However, many authors including Moore and Mein (1975) and Ward (1984), have suggested that a better impression of a model's performance is gained by the use of a number of indices. No one index currently available is considered to be sufficient to define an adequate fit. Consequently, in the operational validation of HYMO2 which is undertaken here, a number of both graphical and numerical comparisons are effected.

The procedure which was followed in order to provide an assessment of the accuracy of the calculated hydrograph is illustrated in figure 41. This comprises two stages, the first compares the two hydrographs, and the second analyzes the forecast errors more closely. Primarily, both stages involve a simple graphical comparison, and then a number of numerical indices are calculated. This procedure for hydrograph comparison will now be examined in more detail.

Figure 41 indicates that stage 1 in this procedure involves a comparison of measured and calculated hydrographs. A graphical display of both hydrographs as time series is an essential first step in the comparison. A plot of the calculated against the measured discharge is also useful for identifying those discharges for which a greater degree of bias occurs.

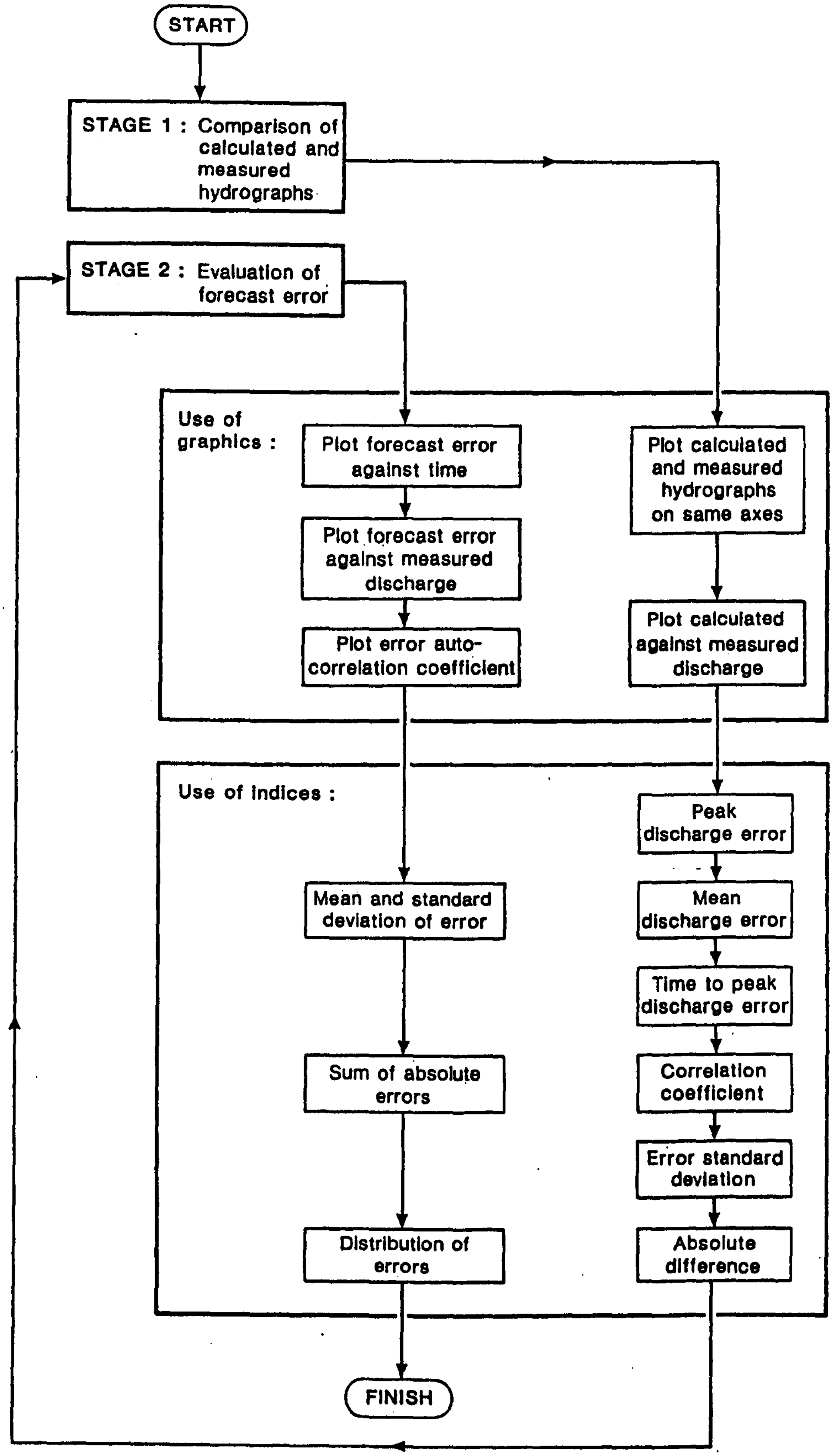


Figure 41: Two stage procedure for hydrograph comparison

As indicated in figure 41, five indices have been selected to assess the goodness of fit. The percentage peak discharge error (PDE) is given by equation (30), the percentage mean discharge error (MDE) is given by:

$$MDE = \frac{(\bar{q}m - \bar{q}c)}{\bar{q}m} \times 100\% \qquad (63)$$

Where:

$\bar{q}m$ - mean measured discharge for the storm event
$\bar{q}c$ - mean calculated discharge for the storm event

and the time to peak discharge error (TPE) is given by:

$$TPE = \frac{(t_pm - t_pc)}{t_pm} \times 100\% \qquad (64)$$

Where:

t_pm - measured time to peak discharge
t_pc - calculated time to peak discharge

A good fit of the calculated to the measured hydrograph will produce a percentage error of these three indices which tends towards zero.

The remaining two formulae provide a quantitative assessment of the overall closeness of fit of the two hydrographs. The formula for the error standard deviation is given by equation (29). A perfect fit will produce an error standard deviation of zero. The correlation coefficient (r) establishes a measure of the association of the measured and calculated hydrographs. The equation is given by:

$$r = \frac{1}{n}\sum_{i=1}^{n}\frac{(qm_i - \overline{qm})(qc_i - \overline{qc})}{\sigma qm \quad \sigma qc} \qquad (65)$$

Where:

σqm - standard deviation of measured discharge
σqc - standard deviation of calculated discharge

A perfect positive correlation for the two series is given by r=1.

Stage 2 of the hydrograph comparative procedure examines more closely the model forecast error (measured minus calculated discharge for each time increment). Examination of error is considered to be important as any further model improvement can only be effected when the source of error, should this prove to be of significance, has been correctly identified (Weber et al, 1973). There are two distinct sources of model forecast error, random and systematic. If the errors are random, and provided that they are small, then a model can be considered to be satisfactory. Where error is systematic, displaying serial correlation, further model modification or restructuring is required to remove the source of this error. The initial step in an analysis of model forecast errors is to plot the errors, for each storm, firstly as a time series, and secondly against measured discharge. To evaluate the degree of serial correlation in the error series, the autocorrelation coefficient is calculated. This provides a numerical assessment of the correlation between pairs of errors (er_i, er_{i+k}), separated by constant interval or lag (k). The estimate of the k th lag autocorrelation coefficient (r_k) is given by:

$$r_k = \frac{(1/n)\sum_{i=1}^{n-k}(er_i - \overline{er})(er_{i+k} - \overline{er})}{(1/n)\sum_{i=1}^{n}(er_i - \overline{er})(er_{i+k} - \overline{er})} \qquad (66)$$

Where:

$\overline{er}$ - mean error

er_i - error

n - number of error measurements in the series

The autocorrelation function is a plot of the autocorrelation coefficient against a range of lags and is sometimes referred to in the literature as a correlogram. An autocorrelation function will be produced for the error series derived from each storm event.

Very basic indices which measure the degree and nature of error include the mean and standard deviation of the error terms for a storm event. Systematic error is manifest in a nonzero mean value and a wide scatter, or large standard deviation. Error which is random will be normally distributed error and it is therefore also of interest to examine the probability distribution of the errors. The test for normality which is applied involves the examination of the normal probability plot of the data. If the data produce a straight line, then normality can be assumed. The correlation coefficient (r) (equation 65) can be used as a measure of the degree of straightness.

The results of the application of HYMO2 will now be presented to determine how well the model replicates the hydrograph response of the North Creek and Sixmile Creek to those 12 storm events which are detailed in table 23. The soils information and iteration period used for each storm is that which provided the closest hydrograph response to the measured in the previous section. Analysis of the results will conform strictly to the procedure illustrated in figure 41.

Stage 1: <u>Comparison of calculated and measured hydrographs</u>

Time series plots of the calculated and measured hydrographs for the six storms applied to the North Creek are provided in figures 42, 43, and 44, and for the six storms applied to the Sixmile Creek, in figures 45 and 46. All hydrographs are drawn to the same scale to aid visual

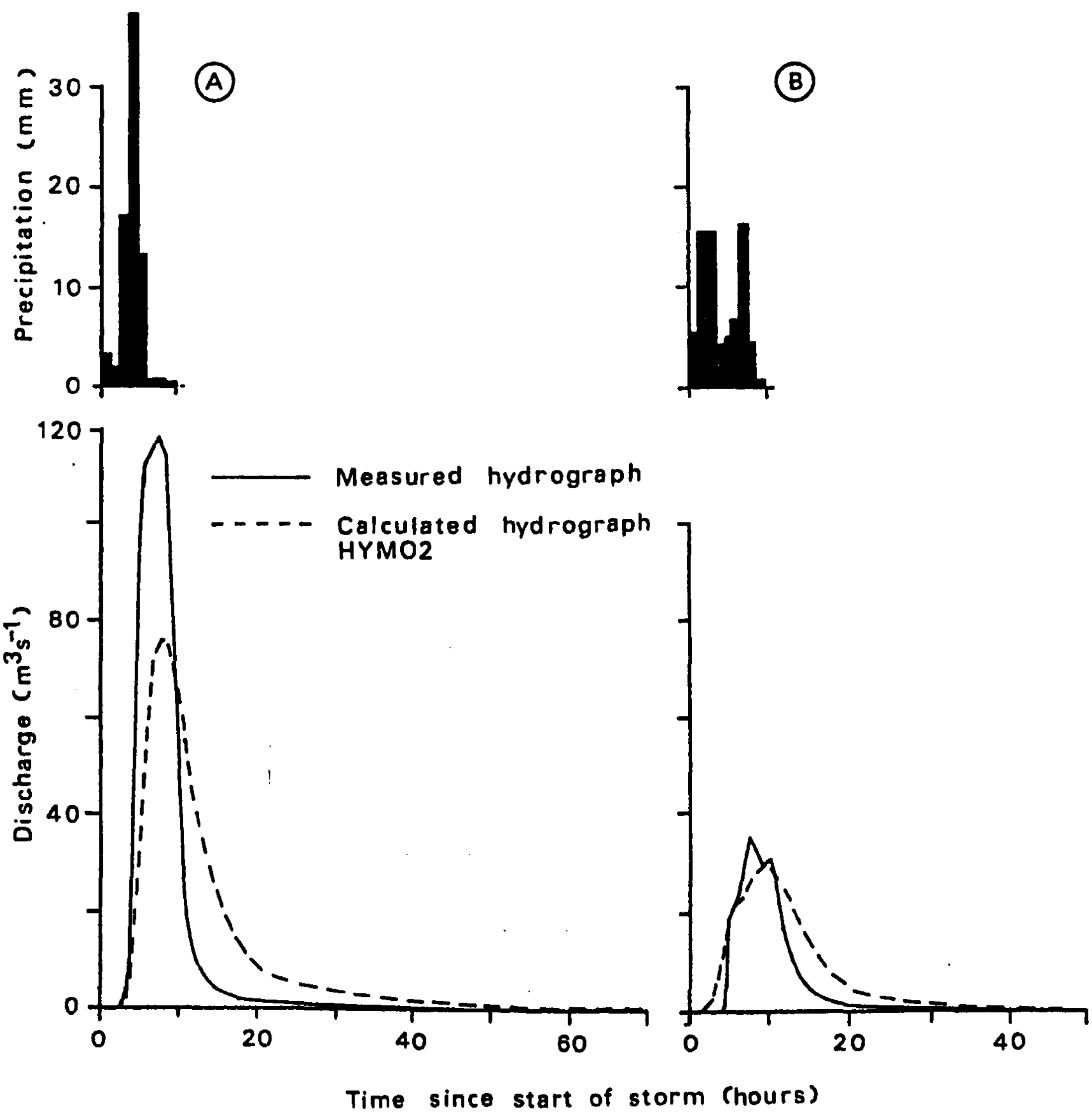


Figure 42 Comparison of calculated and measured hydrographs for the North Creek (A) Storm 1, 9 October 1962 (B) Storm 2, 27 July 1962

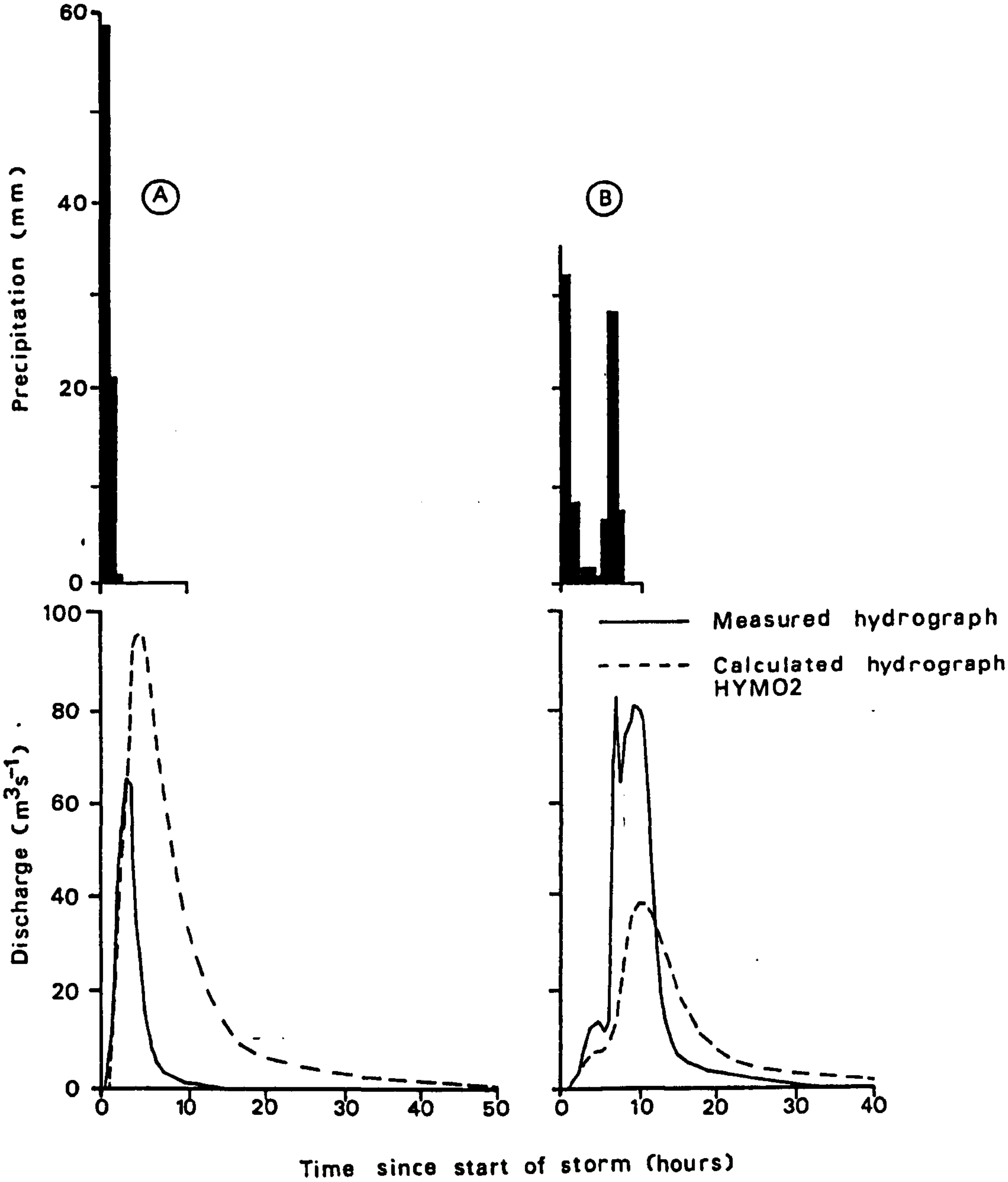


Figure 43 Comparison of calculated and measured hydrographs for North Creek (A) Storm 3, 18 September 1965 (B) Storm 4, 22 April 1966

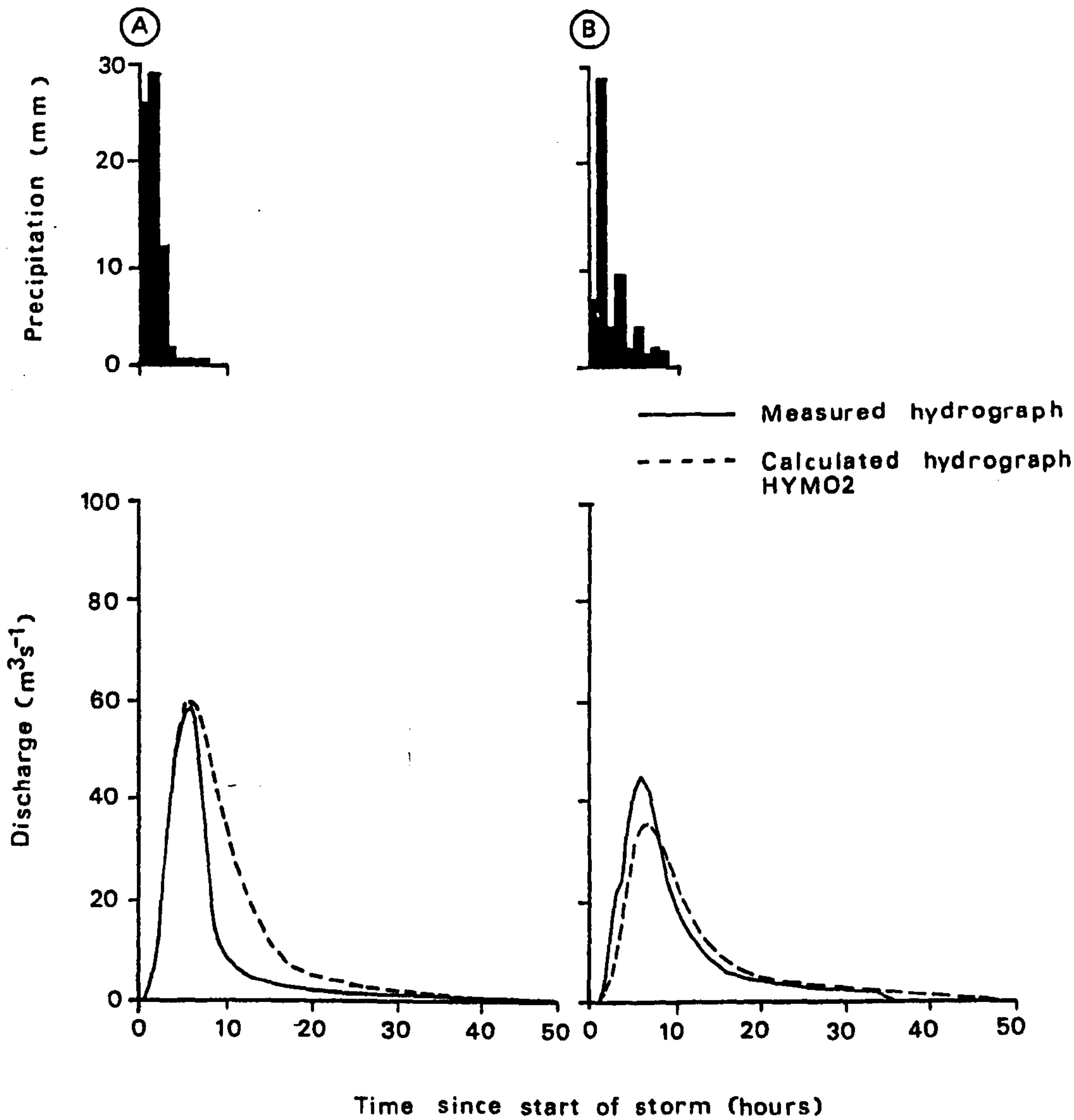


Figure 44 Comparison of calculated and measured hydrographs for the North Creek (A) Storm 5, 4 May 1967 (B) Storm 6, 6 May 1967

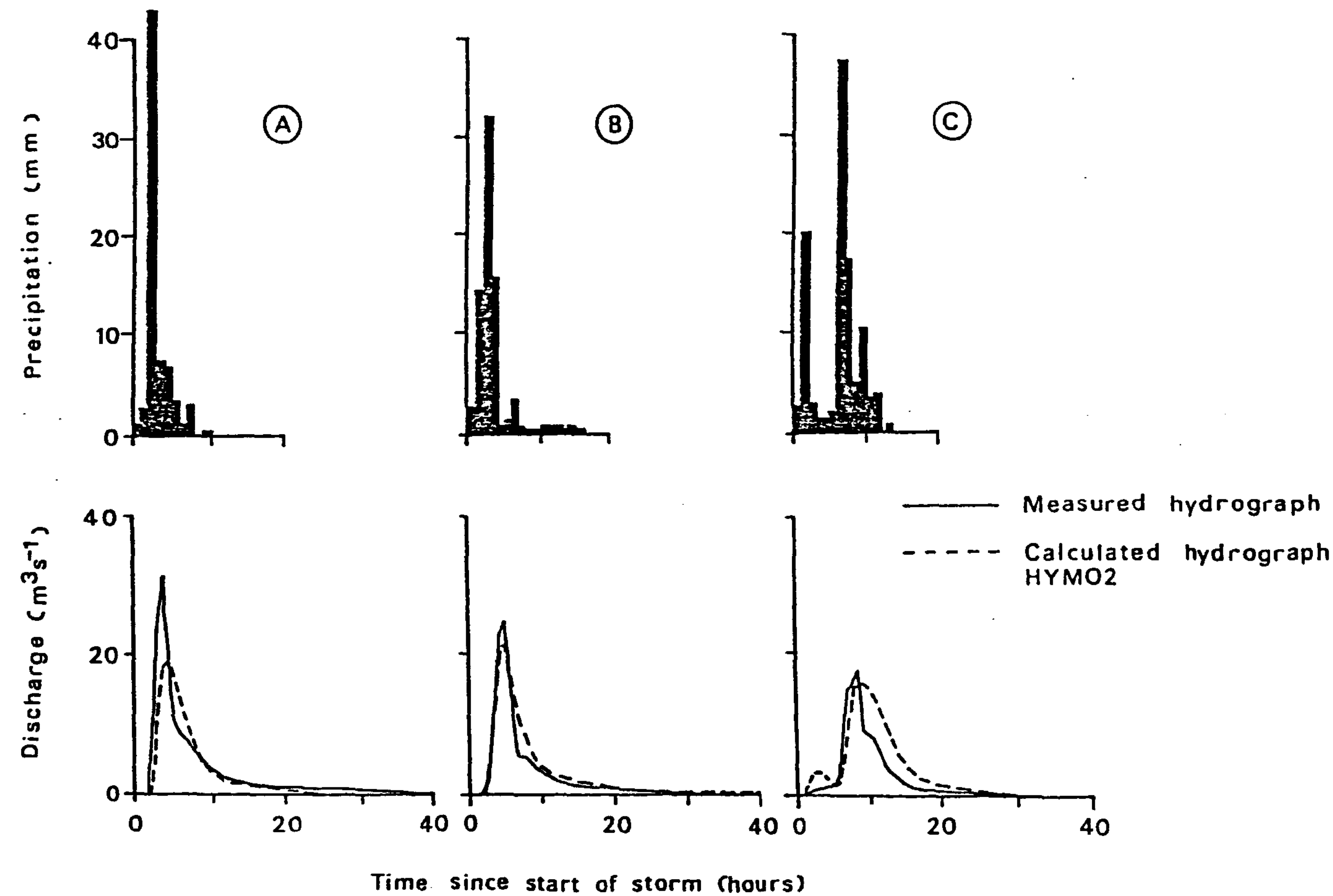


Figure 45 Comparison of calculated and measured hydrographs for Sixmile Creek (A) Storm 1, 20 March 1955 (B) Storm 2, 17 November 1957 (C) Storm 3, 25 June 1958

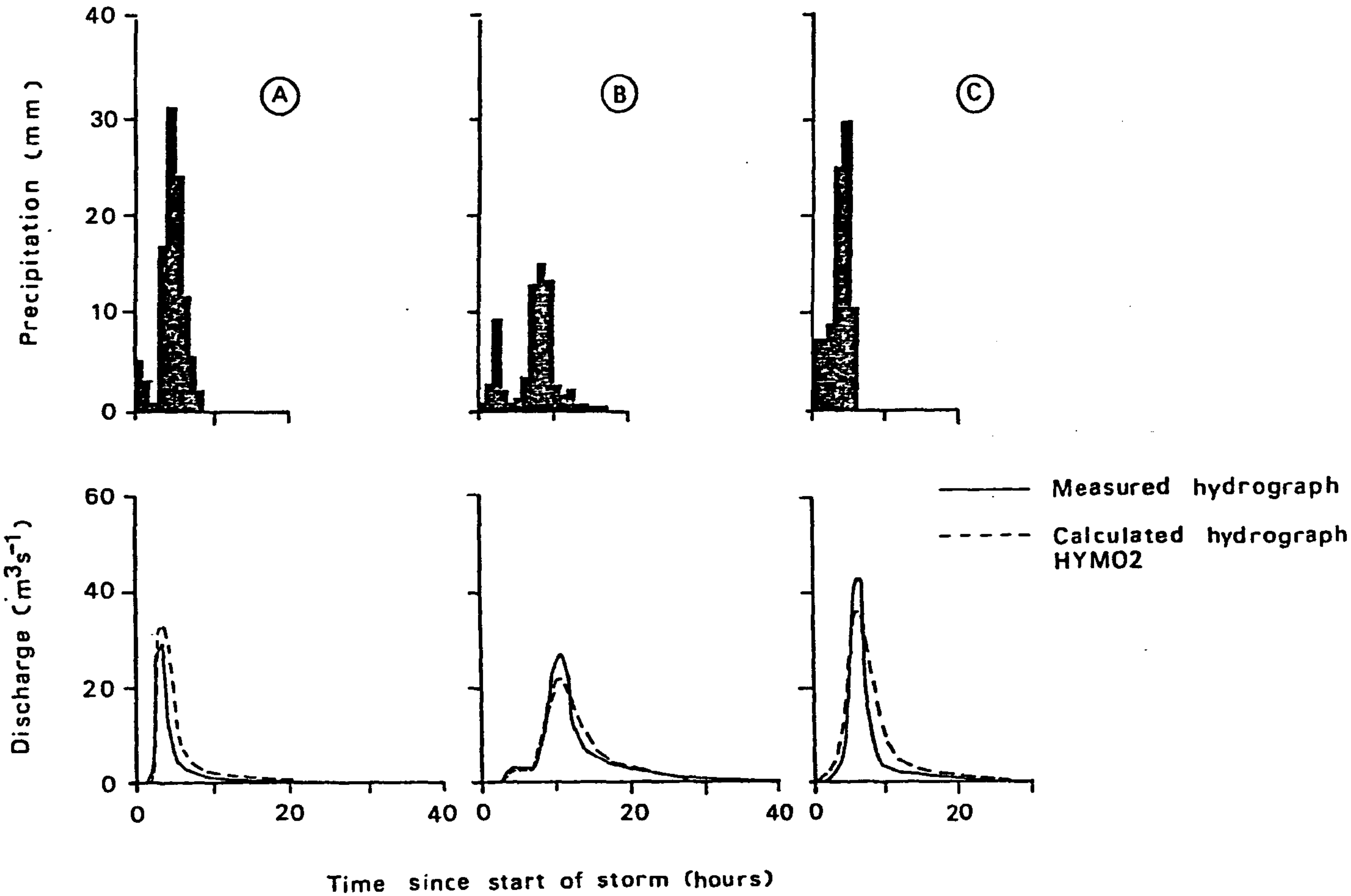


Figure 46 Comparison of calculated and measured hydrographs for Sixmile Creek (A) Storm 4, 3 November 1959 (B) Storm 5, 10 December 1960 (C) Storm 6, 4 May 1961

comparisons. For the 12 experimental frames, the overall measured hydrograph shape is reasonably well approximated by the predictions provided by HYMO2. There does exist a tendency however to overpredict the recession discharges. The highly peaked form of the measured hydrograph is not represented in the predicted. There is also a tendency to underpredict the peak discharge of certain storm events. This occurs for 9 out of the 12 experimental frames. This underprediction is most severe in the North Creek for storm 1 (figure 42(A)) and storm 4 (figure 43(B)). The greatest overprediction of peak discharge also occurs in the North Creek, for storm 3 (figure 43(A)). Much closer approximations to the measured are derived for the Sixmile Creek. The timing of hydrograph rise and peak discharge predicted by the modified HYMO is good for all storms illustrated here, and this is also the case for those storms which exhibit a double hydrograph peak.

A plot of the calculated against the measured discharge is provided by figure 47. Very similar plots are derived from the six storms for each catchment and consequently only two storms (storm 1 for the North Creek, and storm 6 for the Sixmile Creek) are presented here for illustration. The dashed line on each plot indicates the position of perfect prediction and the arrows indicate the order of occurrence of errors from t=0 and at successive time intervals through the storm event. The plot for storm 1, North Creek (figure 47(A)) illustrates clearly the underprediction of the rising limb and peak discharge and as the curve passes the dashed line, the overprediction of the latter stages of the recession. A similar pattern is displayed for storm 6, Sixmile Creek (figure 47(B)) but with an additional period of overprediction in the earlier stages of the hydrograph rise. These two graphs also demonstrate the better predictions which are derived for the Sixmile Creek than for the North Creek as the points on the graph are located closer to the dashed line.

A comparison of the percentage peak discharge error, percentage mean discharge error, and percentage time to peak discharge error, for all 12 experimental frames, is provided by figure 48. More accurate estimates of these particular hydrograph characteristics are derived for the

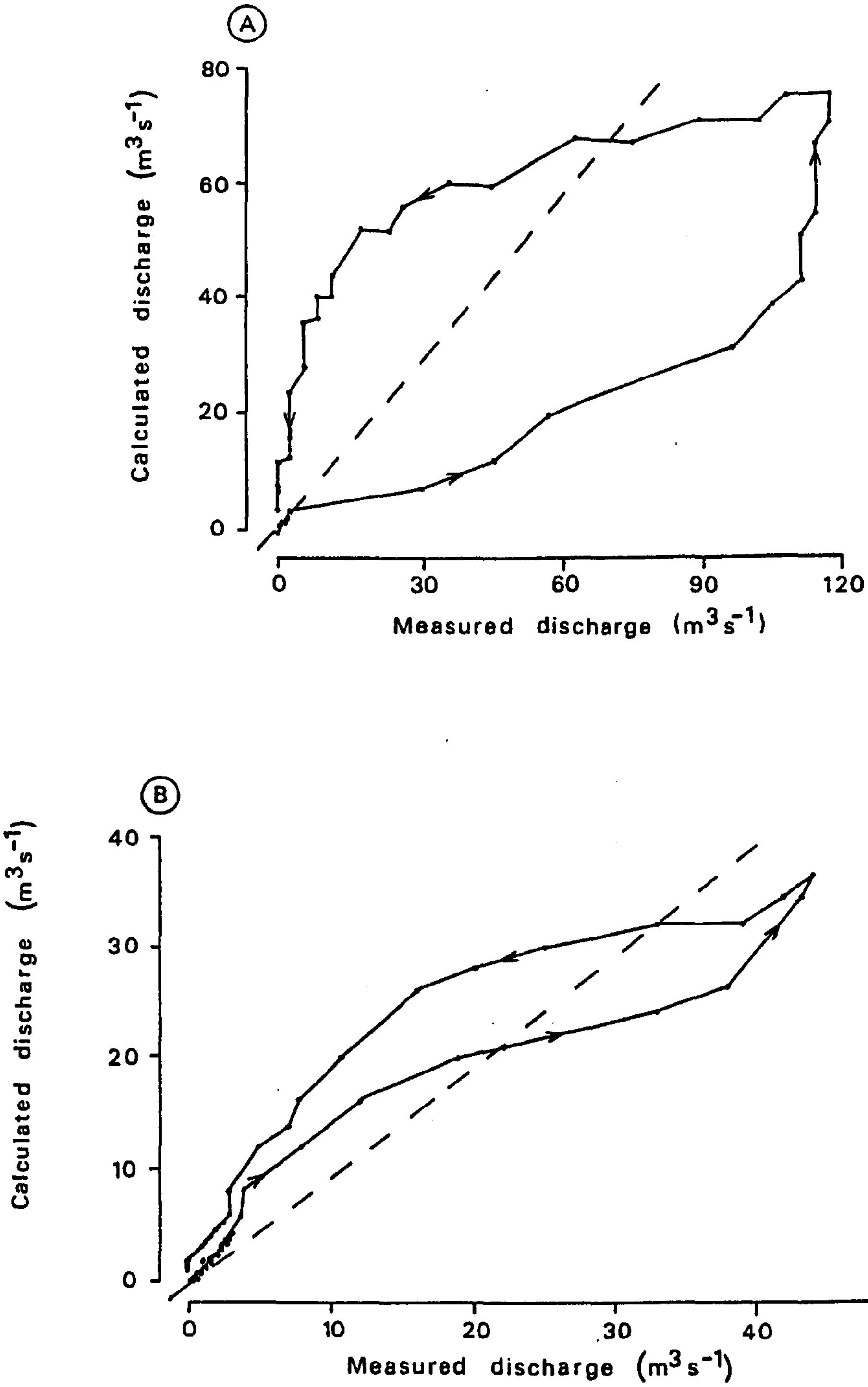


Figure 47: Relationship between discharge predicted by HYMO2 and the measured discharge for (A) Storm 1, 9 October 1962, North Creek (B) Storm 6, 4 May 1961, Sixmile Creek

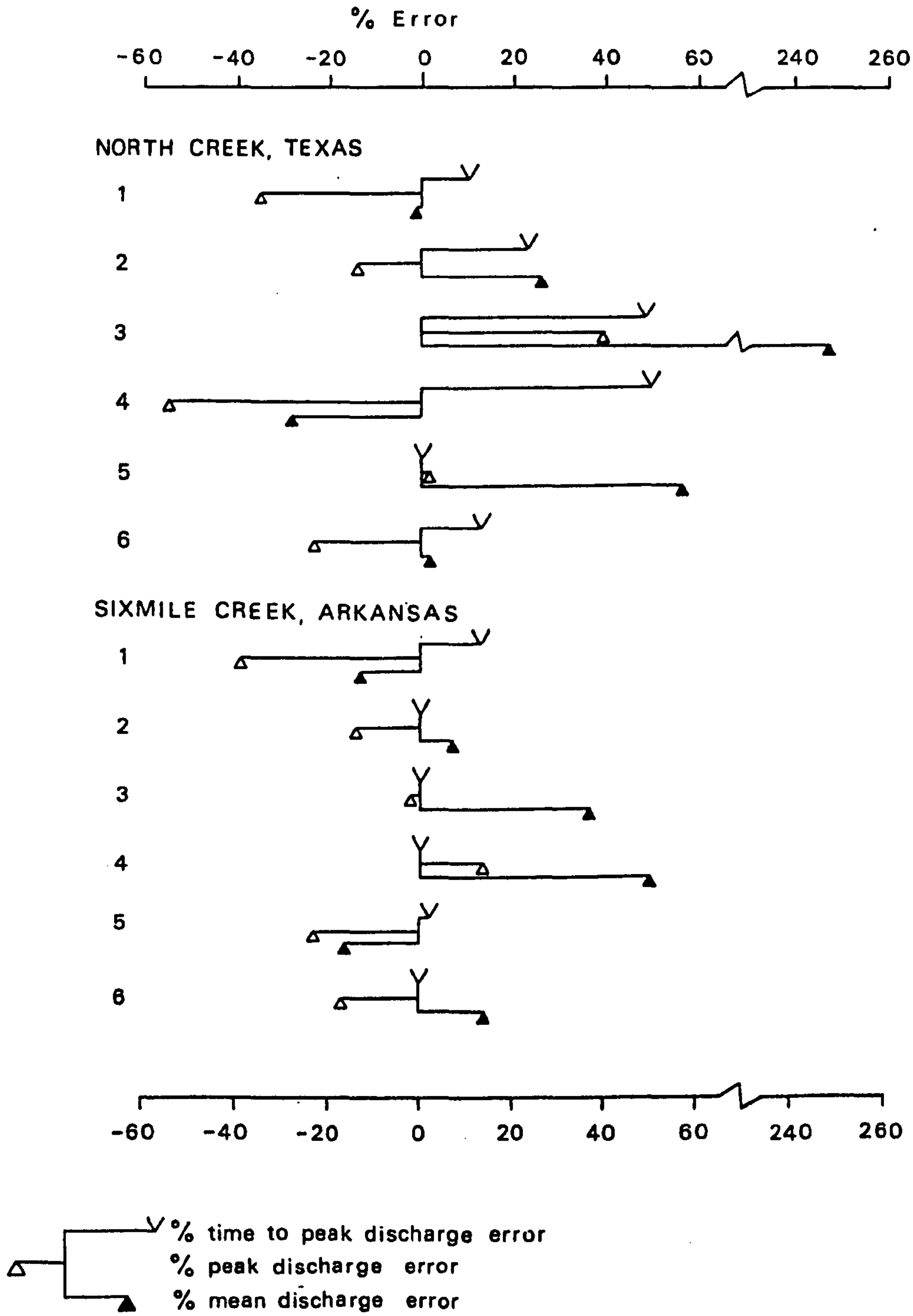


Figure 48: Percentage peak discharge error, percentage mean discharge error, and percentage time to peak discharge error for 12 storms, North Creek and Sixmile Creek

Sixmile Creek than are experienced for the North Creek. Percentage peak discharge error (indicated by the white triangles) ranges from -54% to +40% for the North Creek, and less widely, from -39% to +14% for the Sixmile Creek. Peak discharge is predicted to within 15% of the measured for 5 of the 12 storm events. Percentage mean discharge error (black triangles) ranges very widely from -28% to +245% for the North Creek and between only -16% and +50% for the Sixmile Creek catchment. For only 5 storms of the 12 applied to these two catchments is mean discharge calculated to within 15% of the measured. For eight storms, mean discharge is overpredicted. Time to peak discharge is either exactly or overpredicted for all storm events. The percentage time to peak discharge error ranges rather less widely for both catchments and is of the order 0% to 49% for the North Creek, where time to peak discharge is correctly predicted for one storm, and 0% to 13% for the Sixmile Creek, where the time to peak discharge is correctly predicted for four storms. It should also be noted that for any one storm indicated in figure 48, a good prediction of any one hydrograph characteristic is not necessarily to be associated with the good prediction of the other characteristics. For example, for the North Creek, storm 5 provides good estimates of peak discharge and time to peak, but mean discharge is overestimated by 57%.

The correlation coefficients and error standard deviations calculated for these 12 experimental frames are illustrated in figure 49 and this shows clearly that better forecasts are derived for the Sixmile Creek than for the North Creek where a much greater spread of these indicies is experienced. In addition, it is also interesting to note that these two indices do appear to show a positive correlation with each other. However, the error standard deviation does perhaps more usefully show a greater range between the more and less acceptable predictions.

Stage 2: Evaluation of errors

Plots of model forecast error (measured minus calculated discharge for each time interval) for all 12 storms which have been considered are provided by figures 50 and 51. The differences in vertical scale

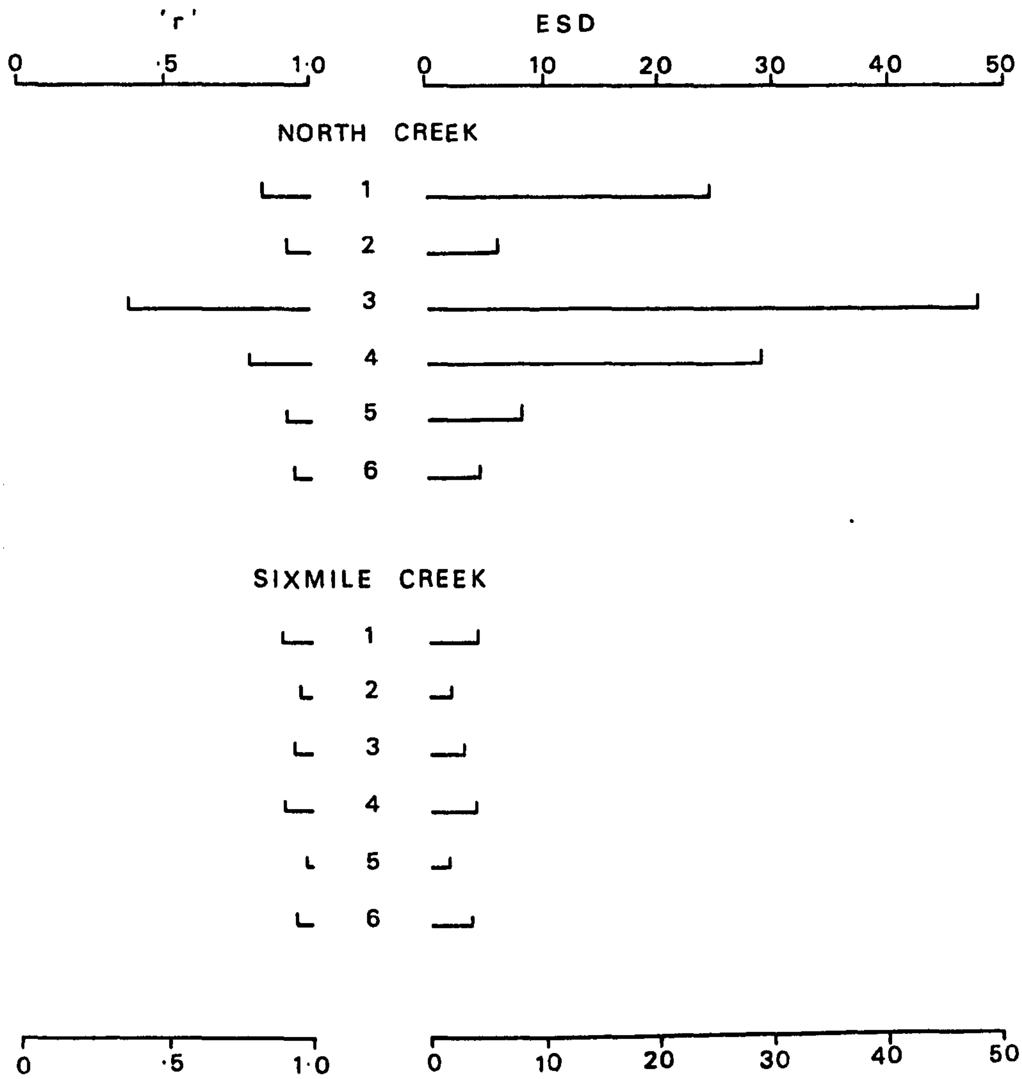


Figure 49: Correlation coefficient (r) and error standard deviation (ESD) for 12 storms, North Creek and Sixmile Creek

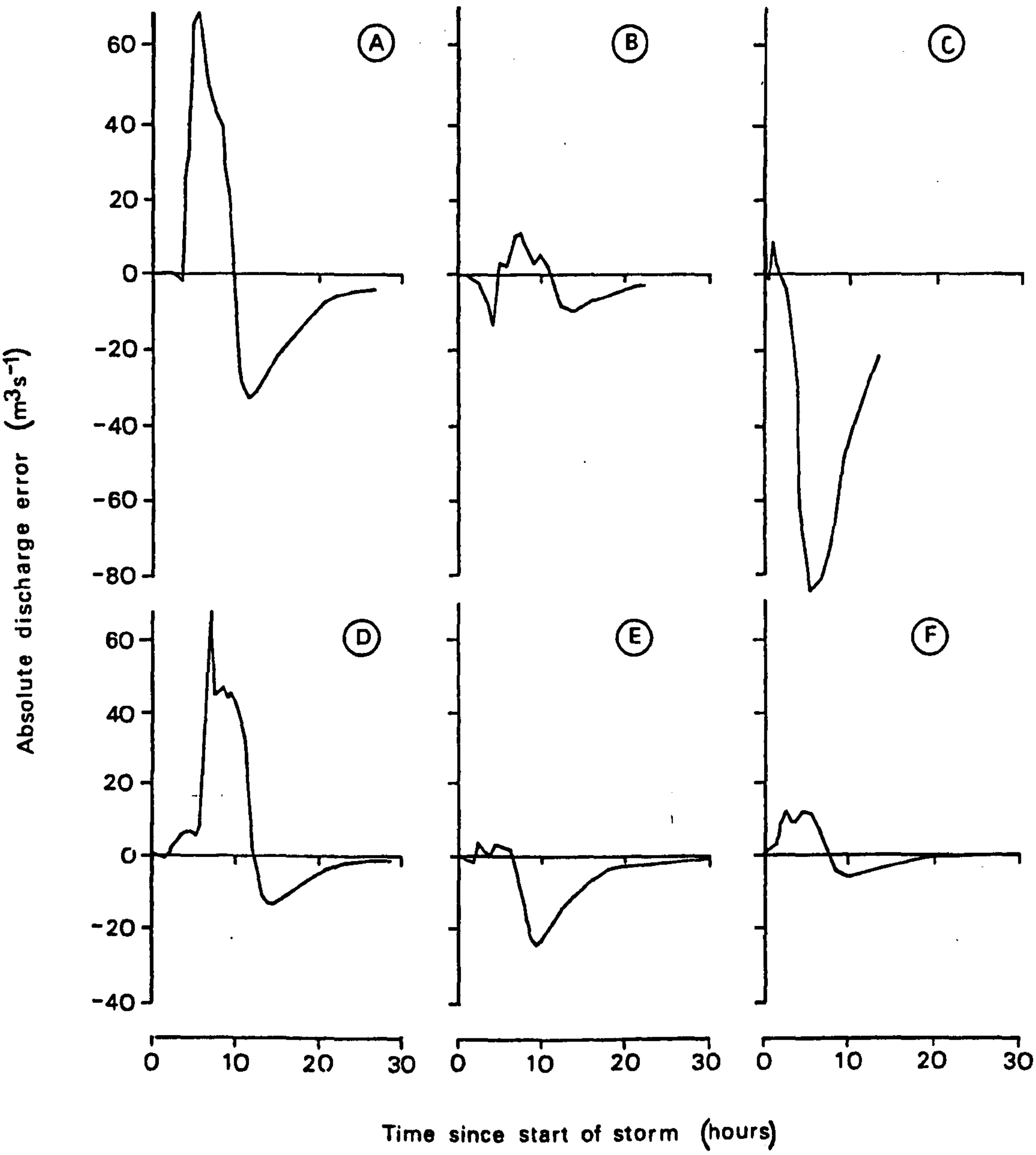


Figure 50: Absolute discharge error for North Creek (A) Storm 1, 9 October 1962 (B) Storm 2, 27 July 1962 (C) Storm 3, 18 September 1965 (D) Storm 4, 22 April 1966 (E) Storm 5, 4 May 1969 (F) Storm 6, 6 May 1969

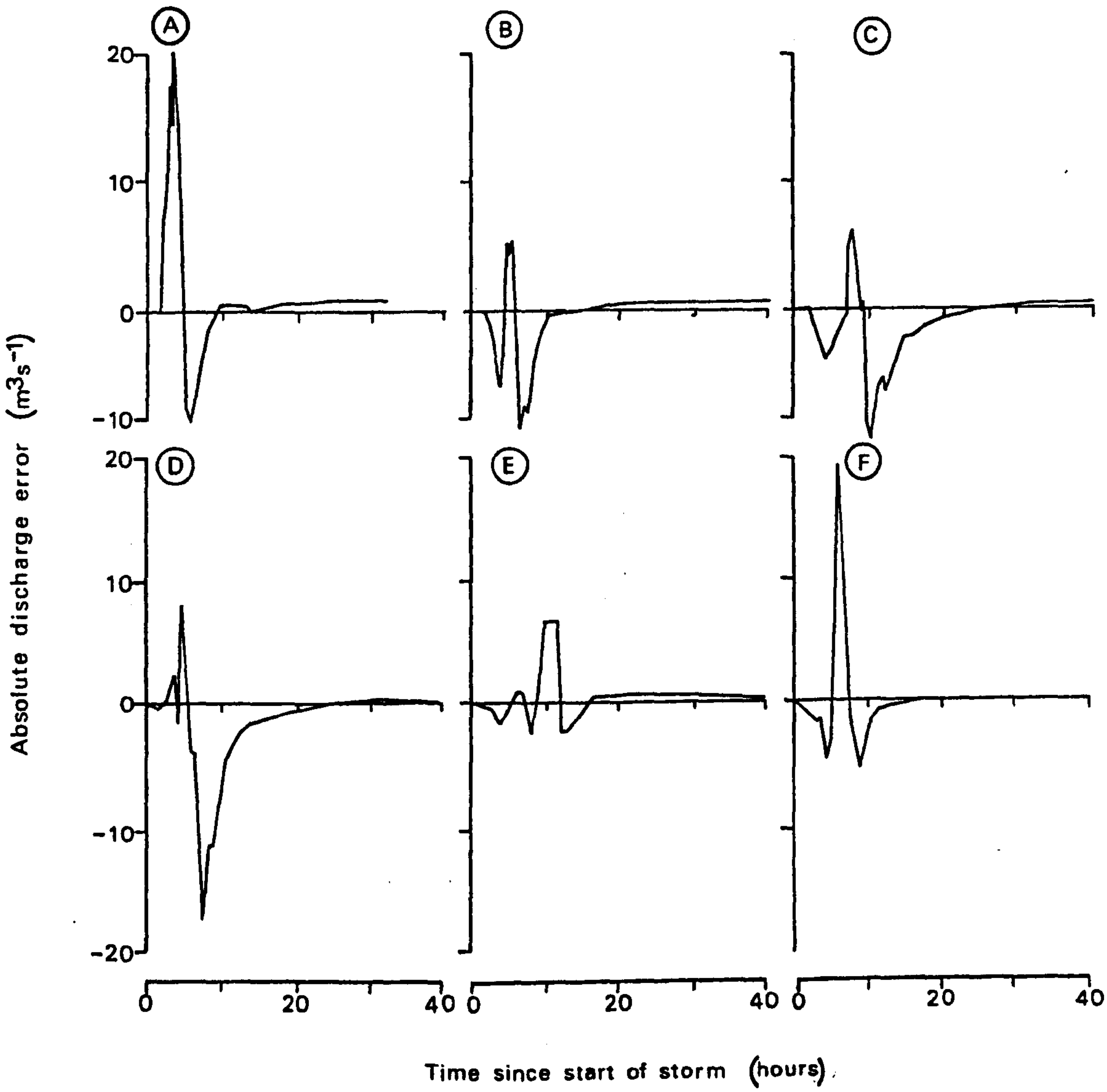


Figure 51: Absolute discharge error for Sixmile Creek (A) Storm 1, 20 March 1955 (B) Storm 2, 17 November 1957 (C) Storm 3, 25 June 1958 (D) Storm 4, 3 November 1959 (E) Storm 5, 10 December 1960 (F) Storm 6, 4 May 1961

between these two figures should be noted; much greater error is associated with predictions for the North Creek. For all 12 storms, there is a tendency to overestimate or underestimate for a period of successive time intervals. The errors do not appear to be random, but display systematic variation. A similar pattern of overprediction (negative error), then underprediction (positive error), and then overprediction is characteristic of the error derived from the application of the six storms to the North Creek. The magnitude of the error varies between storms, but the overall pattern is readily discernible. A very similar pattern is exhibited by the errors derived from the model application to the Sixmile Creek, although the absolute value of the errors is less.

A plot of error versus measured discharge for storm 1 applied to the North Creek and storm 6 applied to Sixmile Creek is provided by figure 52. The arrows indicate the errors derived at t=0 and at successive time intervals through the storm. These plots illustrate more clearly the pattern of errors which occurs during the storm event when HYMO2 is applied, and the consistency of this pattern between storm and catchments.

The autocorrelation function for each storm is plotted in figure 53 for the North Creek, and figure 54 for the Sixmile Creek. These figures confirm the presence of autocorrelation, in the error series. Greater autocorrelation coefficients are associated with worse hydrograph fits. In figure 53 for example, the autocorrelation coefficient remains positive for lags of up to 19 for storm 3. This storm is very poorly predicted by the modified HYMO. The autocorrelation coefficients are lower for the Sixmile Creek where the curve does tend to approach zero.

The mean and standard deviation of the errors is provided by figure 55. The mean of errors is much closer to zero for the Sixmile Creek than for the North Creek, which indicates the better predictions which are derived for this catchment. Quite wide deviations from zero are exhibited by the mean errors for the North Creek, and especially for storms 1, 3, and 4.

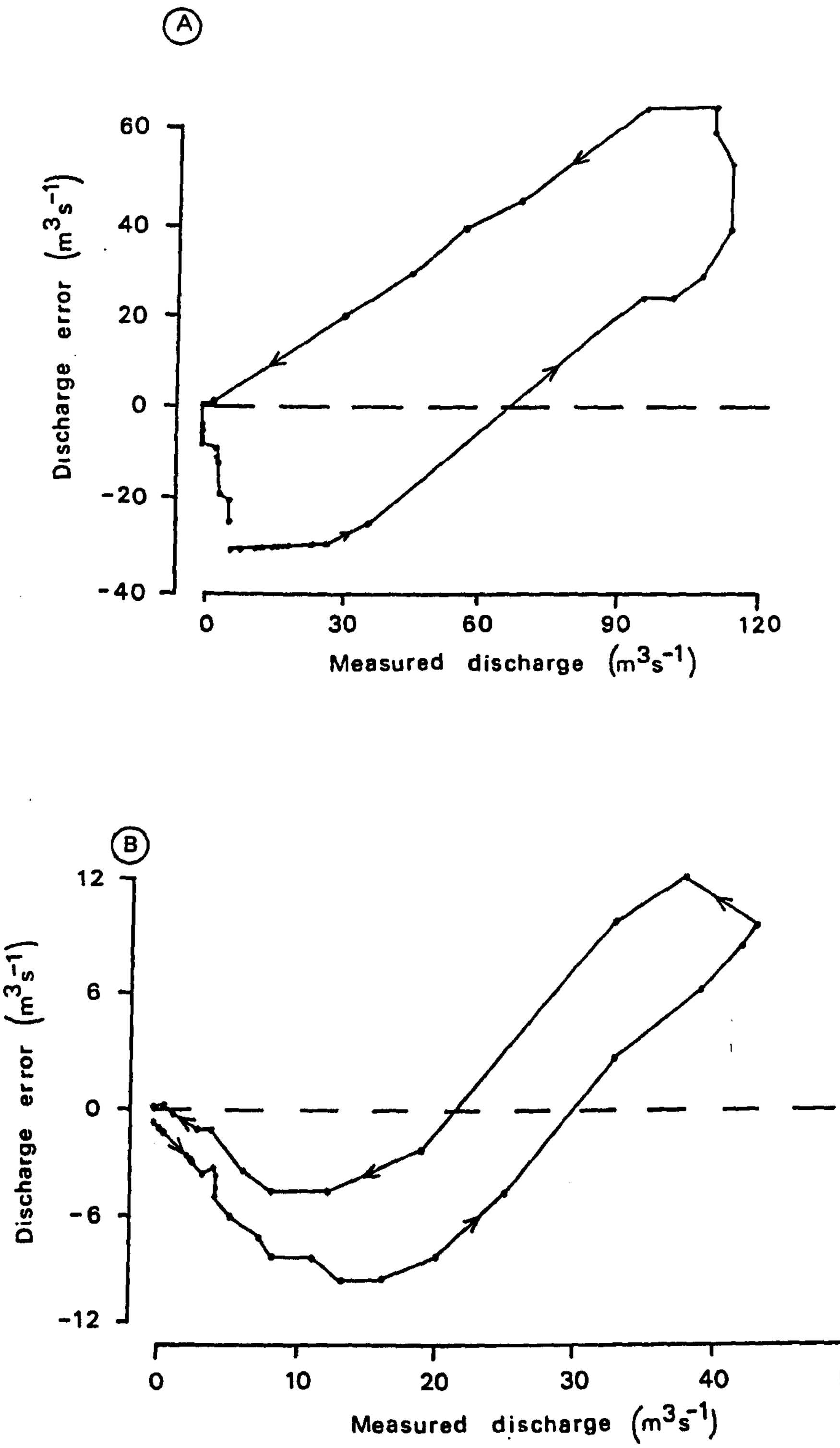


Figure 52 Relationship between measured discharge and discharge error provided by HYMO2 for (A) Storm 1, 9 October 1962, North Creek (B) Storm 6, 4 May 1961, Sixmile Creek

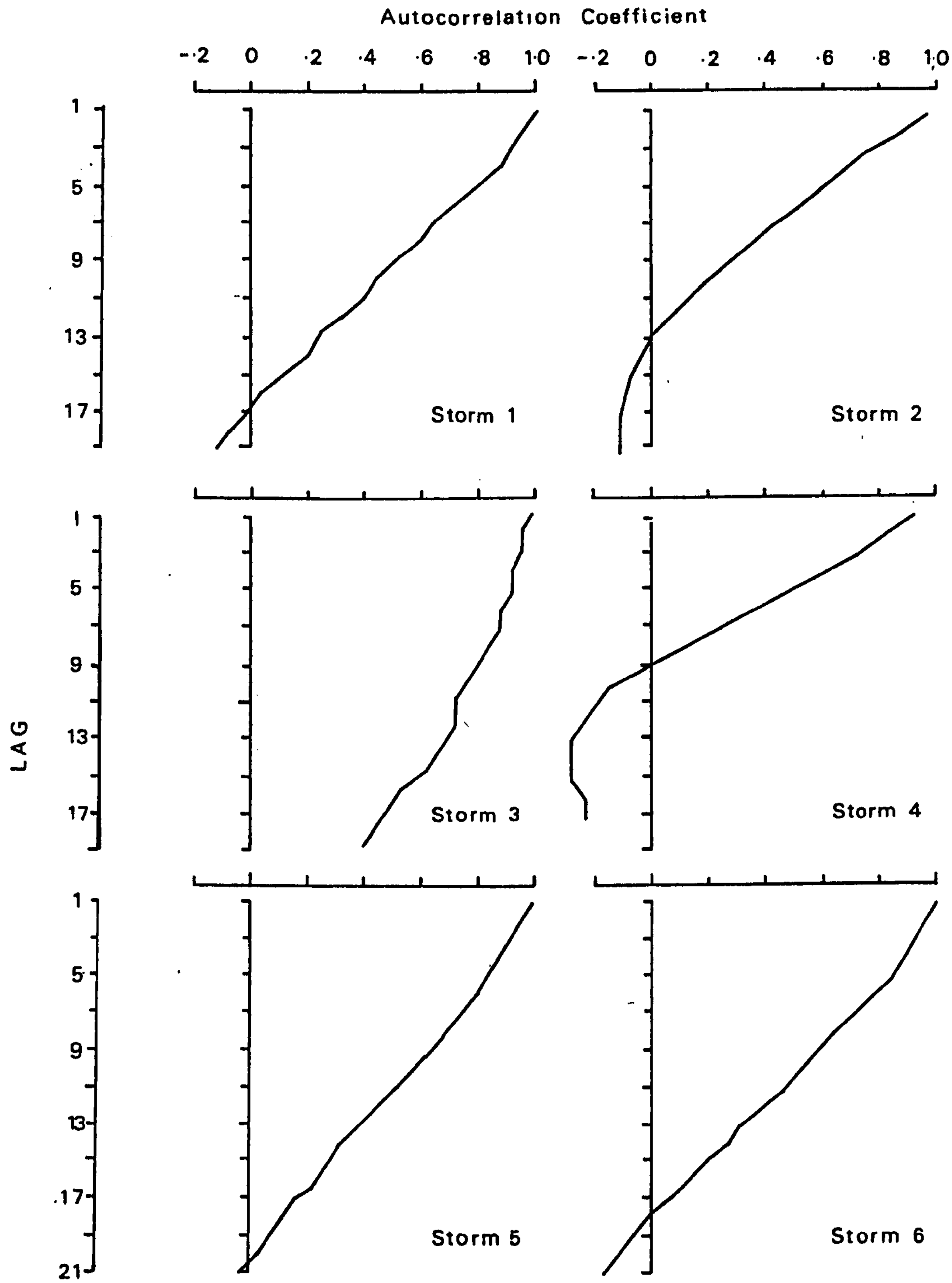


Figure 53 Autocorrelation coefficients for discharge error provided by HYMO2 for 6 storms, North Creek

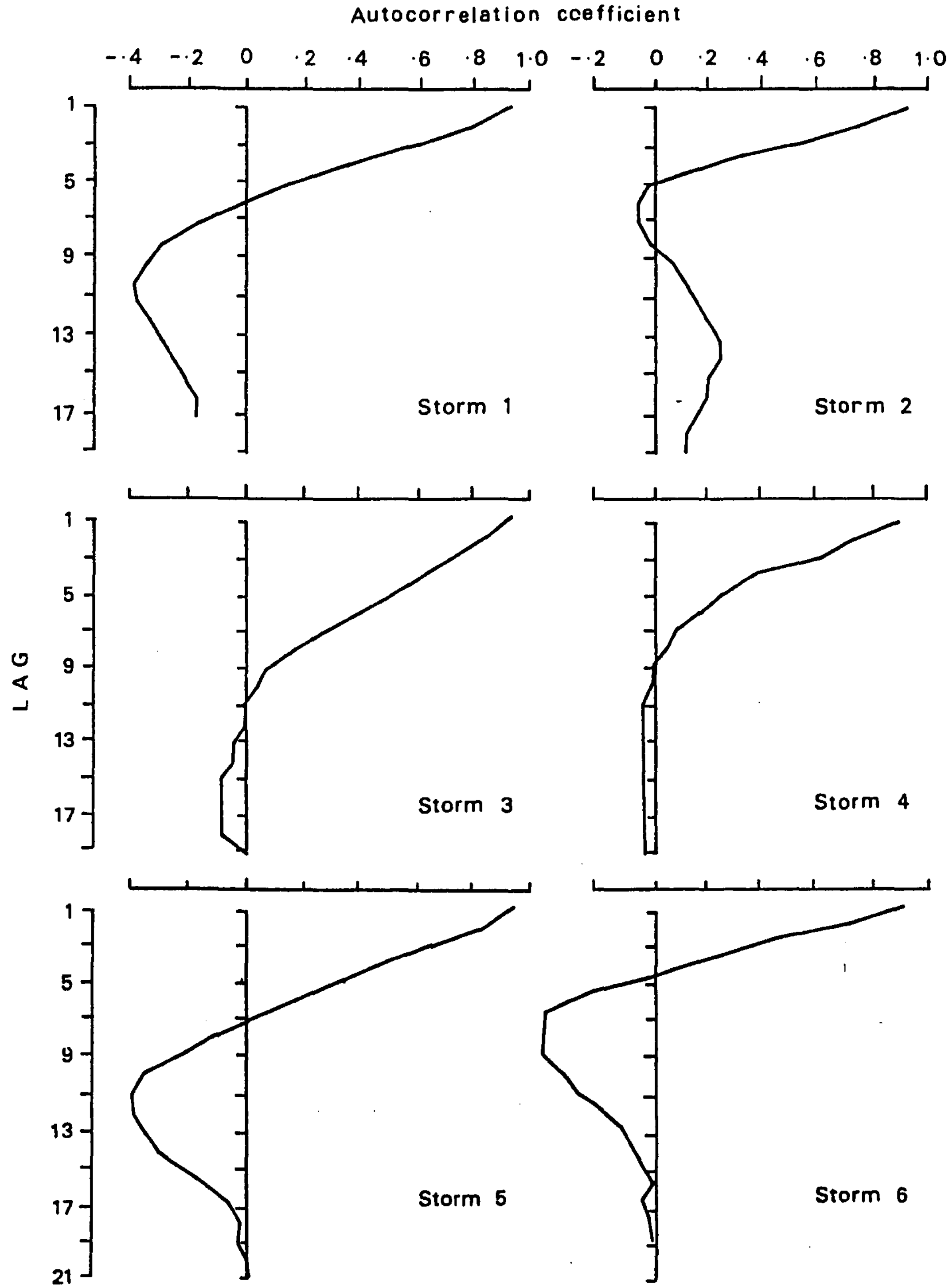


Figure 54 Autocorrelation coefficients for discharge error provided by HYMO2 for 6 storms, Sixmile Creek

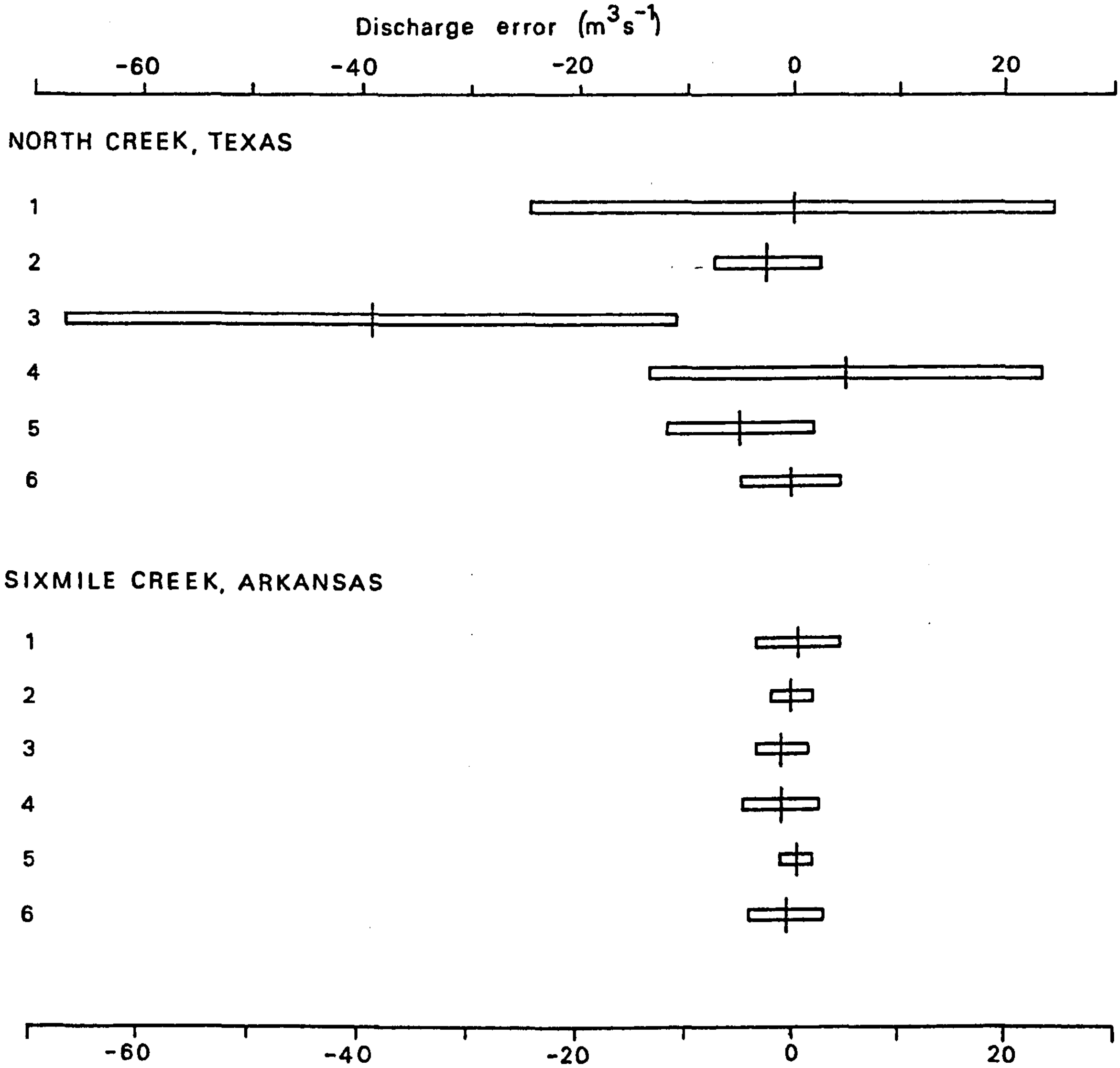


Figure 55 The mean (vertical line) and one standard deviation (horizontal bar) of discharge error provided by HYMO2 for 12 storms, North Creek and Sixmile Creek

The distribution of errors, for each storm, was analyzed for normality by calculating the correlation between errors and normalized errors. These correlation coefficients are presented in table 30. None of the 12 calculated values exceeded the value for 95% significance and so the errors are not to be considered to be normally distributed.

In conclusion therefore, HYMO2 appears to operate more successfully for the Sixmile Creek than for the North Creek. The disparities between the calculated and measured hydrographs vary much more widely, and are consistently greater for the North Creek than for the Sixmile Creek.

Error in prediction is exhibited for both catchments, and this error has been demonstrated to be systematic. There are many potential sources of error, and two will be considered here:

1. <u>Error which is inherent in any mathematical representation</u>
This error may be considered to have two components. Firstly, that associated with the hydrologist's interpretation, or deliberate choice of interpretation, of reality. Secondly, that involved in our ability to represent this interpretation in terms of mathematical equations, boundary conditions and simulation techniques. Error will have been introduced into the predictions which HYMO2 is able to produce by the very simplified interpretation of catchment hydrological processes which occur in the catchment, which it has been necessary to assume in order to meet the operational and ungauged requirement established for this study. Error can also be associated with the simplifying assumptions which have been made in order to formulate the mathematical descriptions of infiltration and overland flow.

2 <u>Error in the data which have been used for operational validation</u>
No attempts have been made in these model applications to validate the data. Many, who are involved in modelling studies, would recommend that data validation is an essential step in model evaluation. However, due to the nature of the data which are available for the ungauged catchment, it was considered to be relevant to validate the model with data of similar quantity and quality which would be expected for the

Table 30: Correlation coefficients for normal probability plot of error for all storms applied to North Creek and Sixmile Creek

	Correlation coefficient					
	Storm numbers					
	1	2	3	4	5	6
North Creek Texas	0.829	0.684	0.332	0.924	0.029	0.586
Sixmile Creek Arkansas	0.779	0.788	0.910	0.786	0.831	0.890

No coefficient in this table is statistically significant at the 95% significance level.

proposed model application. The use therefore of quite small scale topogaphic and soil maps, and the derivation of soil hydrological properties from the Brakensiek and Rawls information will have introduced error into the model predictions. It has been noted that the rain gauges which provided the precipitation data for the North Creek and Sixmile Creek are located 11.26 and 9.65 km respectively from the North Creek and Sixmile Creek catchments. The horizontal extrapolation of precipitation information will introduce an additional source of error. An estimate of the possible magnitude of error associated with horizontal extrapolation of pecipitation data is provided by figure 56. This figure is taken from the USDA SCS (1972, figure 4.4) and provides an estimate of the range of error which is likely to occur nine times out of ten when rainfall from a single gauge is used for a catchment located some distance away. The positive error is read directly from the y axis, and the negative error equals half the positive. Figure 57 indicates the range of precipitation totals which are therefore associated with each storm utilized in this section, for both catchments.

The application of HYMO2 to six storms in the North Creek and six storms in the Sixmile Creek have been reported in this section. These applications provide evidence of a systematic pattern of error in discharge predictions for each storm event. The pattern (rather than the magnitude) of the discharge forecast error remains consistent over a range of experimental frames and appears to be independent of catchment and storm characteristics. It is therefore suggested that the source of this error is an inadequacy in the model structure. Error in either catchment or precipitation data would not be expected to produce such a consistent pattern of error over the wide range of experimental frames. The dimensionless unit hydrograph procedure is considered to be one of the most probable causes of this model error. Despite the improvements in runoff prediction which have been derived from the application of the physically based infiltration model, the form of the empirical dimensionless unit hydrograph (figure 9(A)) causes peak discharge to be consistently underestimated and the discharge, during hydrograph recession, to be overpredicted.

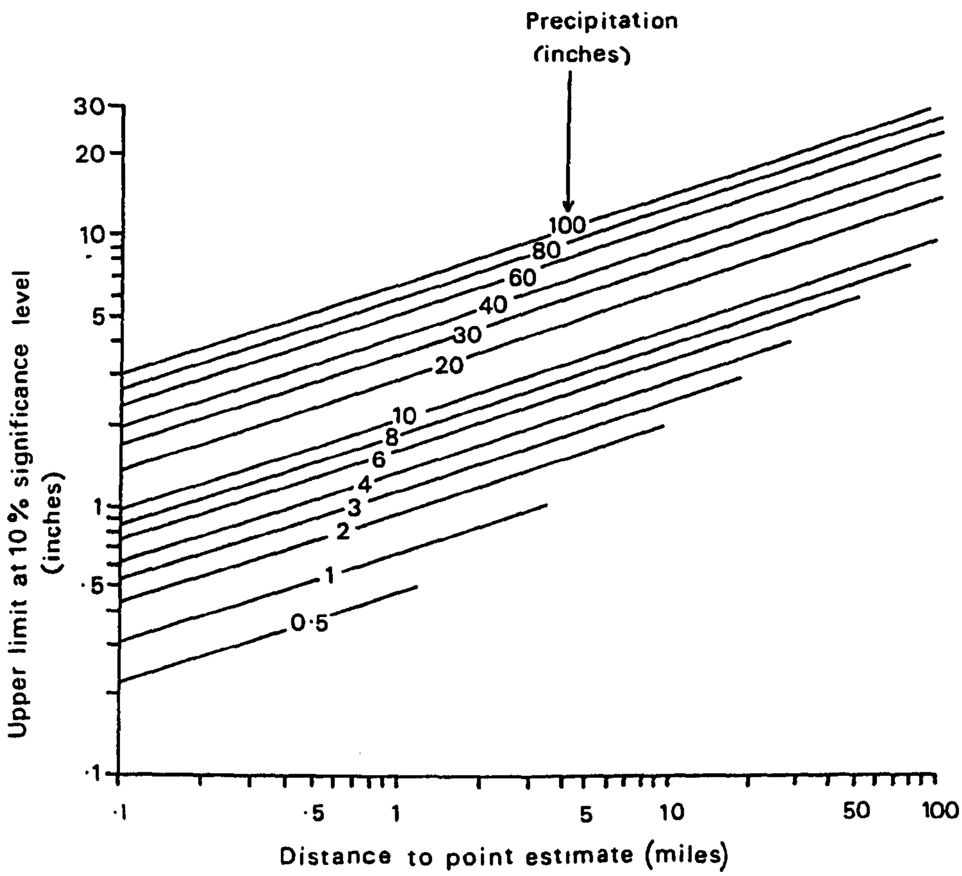


Figure 56 Estimate of error associated with horizontal extrapolation of precipitation data (after USDA SCS, 1972, figure 4.4)

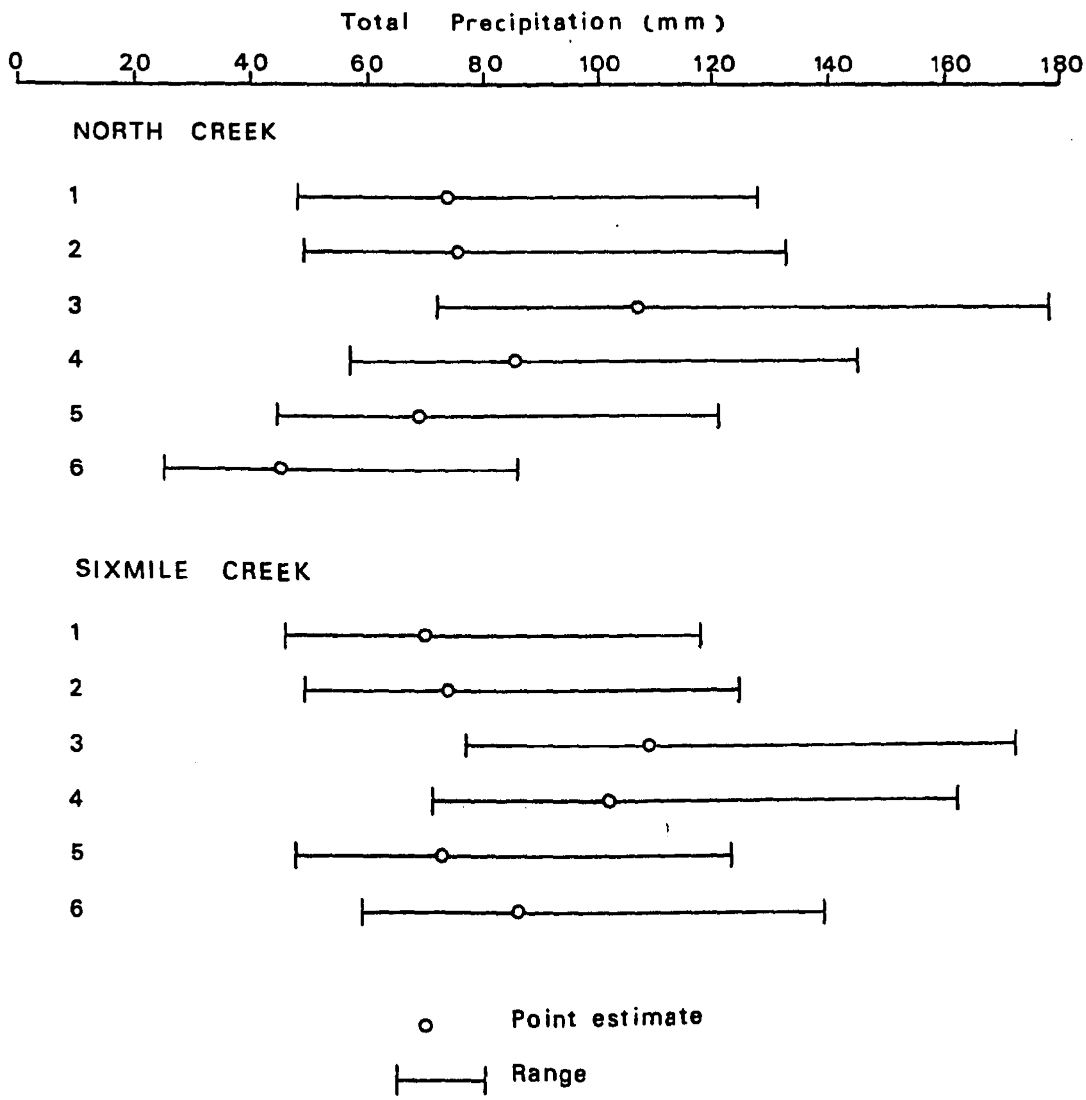


Figure 57 Range of precipitation totals associated with 12 storms, North Creek and Sixmile Creek

It has been illustrated that HYMO2 does provide very reasonable predictions of the discharge hydrographs of the Sixmile Creek, although a greater scatter of predictions are provided for the North Creek.

5.3 Application of the stochastic implementation of HYMO2

Having established the utility of the incorporation of the deterministic infiltration model into HYMO, it is important to establish whether improved hydrograph predictions could be provided by application of the stochastic implementation of the infiltration model. The following question was therefore posed in section 2.5.

Does application of the stochastic implementation of HYMO2, which incorporates an estimate of the spatial variability of soil hydrological properties, significantly improve hydrograph predictions?

The stochastic model was applied to the North Creek catchment to two storms, 1 and 6. The soil hydrological data which provide the best approximation to the measured hydrograph (subsection 3.3.1) was taken as the mean value for each input parameter. The standard deviations were derived from the literature; saturated soil moisture content and the soil moisture characteristic curve from Rawls et al (1982); and saturated hydraulic conductivity and initial relative saturation from Hillel (1977).

Twenty repetitions of the model were made for each storm, and figures 58 and 59 illustrate the form of the generated hydrographs. A wide range of variation is displayed. Table 31 illustrates that the mean value provided by the 20 hydrographs provides estimates which are not as close to the measured, as those derived from the deterministic model. In addition, the stochastic model requires 20 times as much computer time and disc storage for data areas, and soils information which characterizes the variability of soil hydrological parameters. The extra effort involved in the application of the stochastic

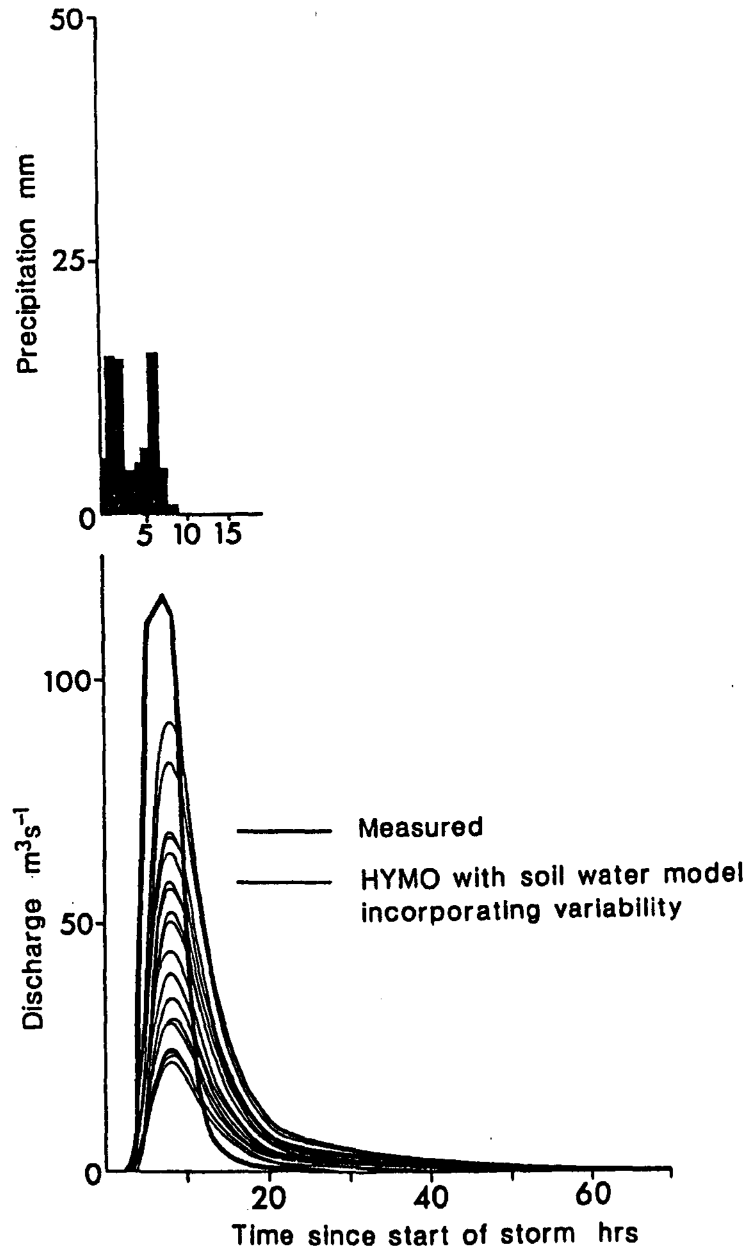


Figure 58 Distribution of hydrographs derived from the application of the stochastic infiltration model in HYMO2 for storm 1, 9 October 1962, North Creek

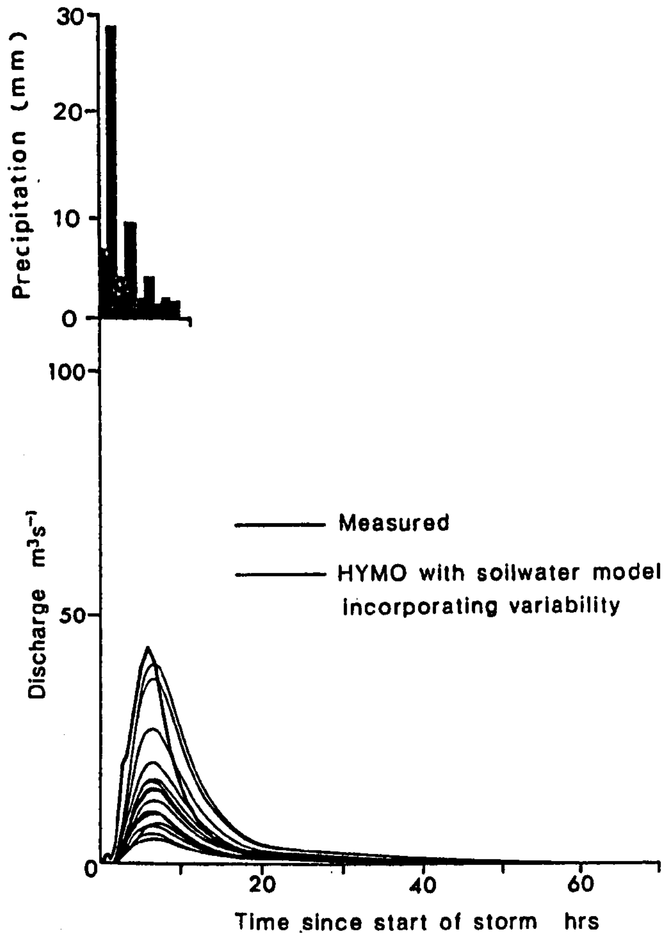


Figure 59 Distribution of hydrographs derived from the application of the stochastic infiltration model in HYMO2 for storm 6, 4 May 1961, Sixmile Creek

Table 31: Comparison of hydrograph predictions derived from the deterministic and stochastic infiltration model for storms 1 and 6, North Creek, Texas

	Measured	Deterministic model	Stochastic model
Storm 1 9 October 1962			
Runoff volume (mm)	40.0	38.0	27.0
Peak discharge ($m^3 s^{-1}$)	117.0	76.0	48.0
Time to peak (hours)	7.2	8.0	7.9
Error standard deviation	-	25.0	31.1
% peak discharge error	-	35.0	54.0
Storm 6 6 May 1969			
Runoff volume (mm)	18.0	17.5	10.5
Peak discharge ($m^3 s^{-1}$)	44.0	33.0	18.0
Time to peak (hours)	5.8	6.5	6.8
Error standard deviation	-	4.5	8.6
% peak discharge error	-	23.0	59.0

implementation of HYMO2 does not provide improvements to the hydrograph predictions of the deterministic version of HYMO2.

This chapter has provided details of the application of HYMO2 to two catchments in Texas and Arkansas and the potential operational validity of HYMO2 has been illustrated. The following chapter proceeds with the further application of HYMO2 to five catchments in Vermont and Iowa.

6

Application of HYMO2

Certain results of the application of HYMO2 to the North Creek catchment, Texas and the Sixmile Creek catchment, Arkansas, have been presented in chapter 5 in the context of operational validation. Application to these catchments was used firstly to illustrate the suitability of the Brakensiek and Rawls empirical information for the derivation of the soils data necessary to operate the model quite successfully for the ungauged catchment, secondly to illustrate a favourable comparison of calculated to measured hydrographs for certain experimental frames, and thirdly to illustrate that improved predictions are not derived from application of the stochastic version of the infiltration model. The deterministic version of HYMO2 is thus considered to be operationally valid for the variety of conditions which have been considered so far. However, it is important to extend this range of application and consequently, the details of the application of HYMO2 to a further five catchments in Vermont and Iowa, United States of America are provided in this chapter. In addition, these applications will provide information for discussion of the following points:

1 Is HYMO2 of a form which is suitable for application to the ungauged catchment?

   The runoff procedure which has been introduced in chapter 2 is not a simple calibrated procedure, but is physically based. Much of the original, and so far undeveloped, model however, does remain calibrated and the issue of the validity of extrapolation of results which have been produced by calibration to other gauged catchments must be raised.

2 Can HYMO2 meet an operational requirement?

Operational requirements were discussed in section 1.2. It has already been established that HYMO2 can be ported onto a microcomputer system. Application will reveal whether or not the model will run at acceptable speeds on this hardware configuration. In addition, the following questions must be considered:

a Are the data preparation requirements reasonable in the context of a potential nonprofessional user?

b Can sufficient guidelines be provided for the user in terms of application and interpretation of the model for a range of applications?

c Can the model be made user friendly?

d Is the software reliable for the now expanding range of applications?

3 Does HYMO2 have an appropriate structure for the ungauged and operational application?

The physically based infiltration model which has been developed, although simple, does attempt to attain a balance between a methodology which is scientifically acceptable, and one which remains operationally feasible. The suitability of this choice will be revealed with the application of HYMO2.

In any application, there will be interest in the accuracy of the hydrograph predictions which the model supplies. However, it has been stressed throughout the discussion on model evaluation, that there are other important questions which must also be specifically investigated in order to provide an unskilled user with sufficient information to guide the intelligent use of the model. In addition to a comparison of calculated and measured hydrographs, the following questions must also be addressed during application of HYMO2:

1 What is involved in the data acquisition and preparation stage? A user needs to know the nature of the decisions which must be taken in order to derive the necessary model parameters. It is also important

to assess the likely time period which will be required for data preparation.

2 Is the infiltration behaviour predicted by the physically based infiltration model reasonable for a range of catchment situations? Infiltration behaviour has been examined for a range of hypothetical conditions in section 4.1. It is important to examine its behaviour for more complex soil and precipitation conditions.

3 Is the explicit finite difference method accurate for these more complex soil profile and variable storm conditions? The numerical errors incurred for a range of simple storm and catchment conditions were considered in section 4.3. Again it is important to evaluate these errors for more complex conditions.

Many of these issues have been considered for a number of hypothetical cases in chapters 4 and 5. They are now considered specifically for catchment situations. These three issues: data preparation, infiltration behaviour, and the stability of the numerical solution, have not been discussed in the context of the application to the North Creek and Sixmile Creek catchments. The information derived from these two catchments will therefore be included in those relevant sections.

This chapter will therefore be divided into six sections. Firstly, the five catchments which are to be used in this chapter will be introduced. Secondly, the data collection and preparation which are necessary for the application of HYMO2 to the catchments will be described. In addition, some more general points about this critical stage in model application will be made. Thirdly, a series of comparisons of calculated and measured hydrographs for a range of storms, applied to the five catchments in Vermont and Iowa, will be presented. This comparison will follow the two stage procedure which was proposed in section 5.2, figure 41. Fourthly, the infiltration behaviour which is predicted by the model for the layered soil profiles and more erratic rainfall conditions, experienced by the catchments, will be examined. Fifthly, the numerical errors incurred in the solution of the Richards equation by the explicit finite difference method will be examined. Finally, an attempt will be made to summarize the information derived from all experimental frames which have been used, in order to define those conditions for which the model is, and those for which it is not, appropriate.

6.1 Introduction to catchments

The five catchments documented in this chapter, and which have been used to evaluate the operation of HYMO2 are the following:

1 An unnamed triburary of the Sleepers River catchment, Connecticut River basin, watershed 2 (W-2) in North Danville, Vermont, United States of America.

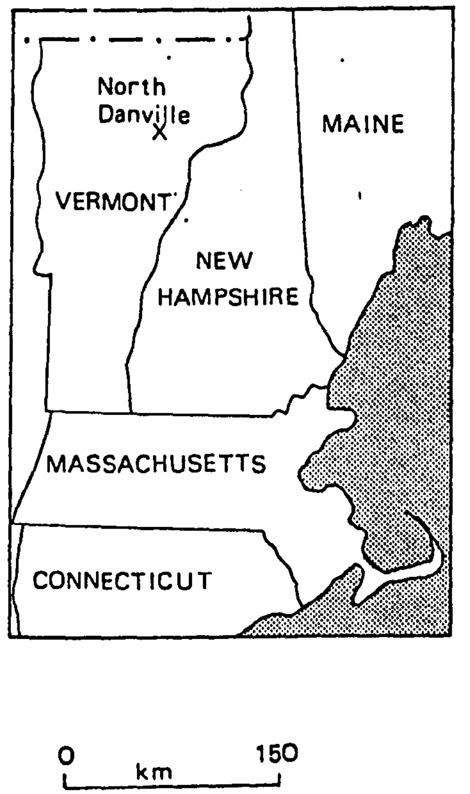
2 Watershed 1 (W-1), Silver Creek, West Nishnabotna River, Missouri River basin, Treynor, Iowa, United States of America.

3 Watershed 2 (W-2), Keg Creek, Missouri River basin, Treynor, Iowa, United States of America.

4 Watershed 3 (W-3), Silver Creek, West Nishnabotna River, Missouri River basin, Treynor, Iowa, United States of America.

5 Watershed 4 (W-4), Silver Creek, West Nishnabotna River, Missouri River basin, Treynor, Iowa, United States of America.

The location of these catchments is indicated in figure 60, and a comparison of the three physical catchment characteristics which are required by the unit hydrograph procedure, is provided by table 32. All of these catchments are small in area (less than 0.6 square km) as this enables a closer examination to be made of the modified runoff component of the model without incorporating the need for channel routing.



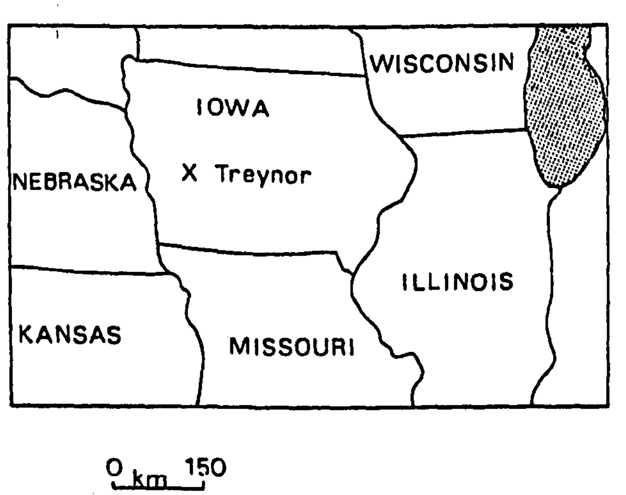


Figure 60 Location of W-2, North Danville, Vermont and W-1, 2, 3, and 4, Treynor, Iowa

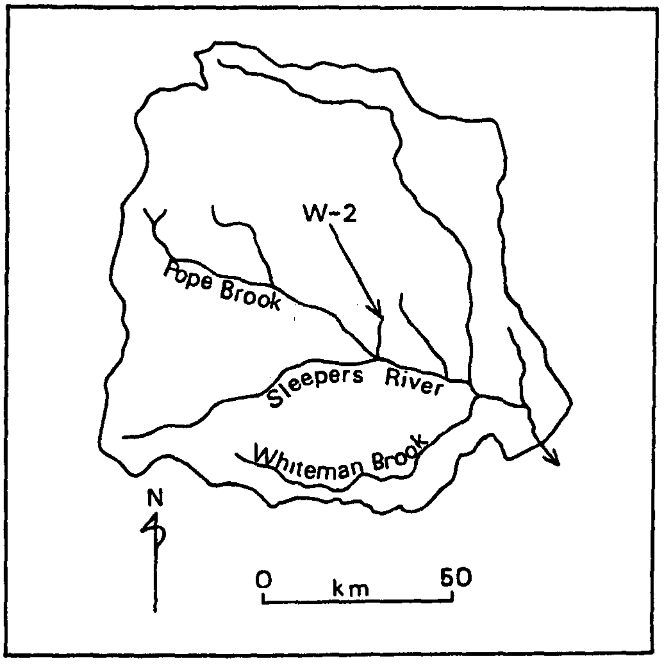
Table 32: Comparison of catchment characteristics which are required by the unit hydrograph procedure

	Area (km^2)	Difference in elevation (m)	Length of main channel (km)
W-2 North Danville Vermont	0.6	79.3	1.2
W-1 Treynor, Iowa	0.3	27.4	1.1
W-2 Treynor, Iowa	0.3	21.3	0.9
W-3 Treynor, Iowa	0.4	27.4	0.9
W-4 Treynor, Iowa	0.6	30.5	0.6

All of these catchments are gauged catchments and are United States Department of Agriculture (USDA) Agricultural Research Service (ARS) experimental watersheds. Hydrological data from all ARS experimental watersheds are currently stored on a data base in the United States, which is accessible by use of REPHLEX (REtrieval Procedures for HydroLogic data from ARS EXperimental watersheds) which has been developed by the Water Data Laboratory and documented by Thurman et al (1983). This data base provides information for 305 watersheds which range from 0.2 ha to 536 square km in area. Precipitation and runoff data for individual storm events and for daily, monthly, or annual accumulations, and which range in length of record from 1 to 45 years are available. Information may be derived from the system in tabular or graphical form. An inventory of the ARS experimental watersheds (Water Data Laboratory, 1983) is published which documents the types of data (precipitation, runoff, pan evaporation, soil moisture, land use, soil survey, for example) which are available for each catchment.

The Sleepers River catchment, Connecticut River basin, Vermont, is located 8.05 km north west of St. Johnsbury. This catchment has been the location of many field studies including Dunne and Black (1970a, 1970b) and it is considered to represent a typical glaciated upland catchment of New England. The location and physical characteristics of the unnamed tributary W-2, are indicated in figure 61. It is described by the USDA as comprising sloping to steep land at higher elevations. It has a covering of glacial till which exhibits good surface drainage and which overlies Devonian schist interbedded with limestone. The land use within the watershed W-2 is divided between permanant hay (37%), pasture (38%), and maple and beech trees (25%).

The four catchments near Treynor, Iowa contain soils which have developed from the deep mantle of Wisconsin loess (3.05 to 27.72 metres) which overlies Kansan glacial till which in turn overlies the bedrock of interbedded calcareous shales and limestones. The watershed topography has developed totally by erosion of loess and the deeper gullies have incised slightly into the till. The loess is considered to have a moderate rate of percolation. In all four watersheds channel flow is



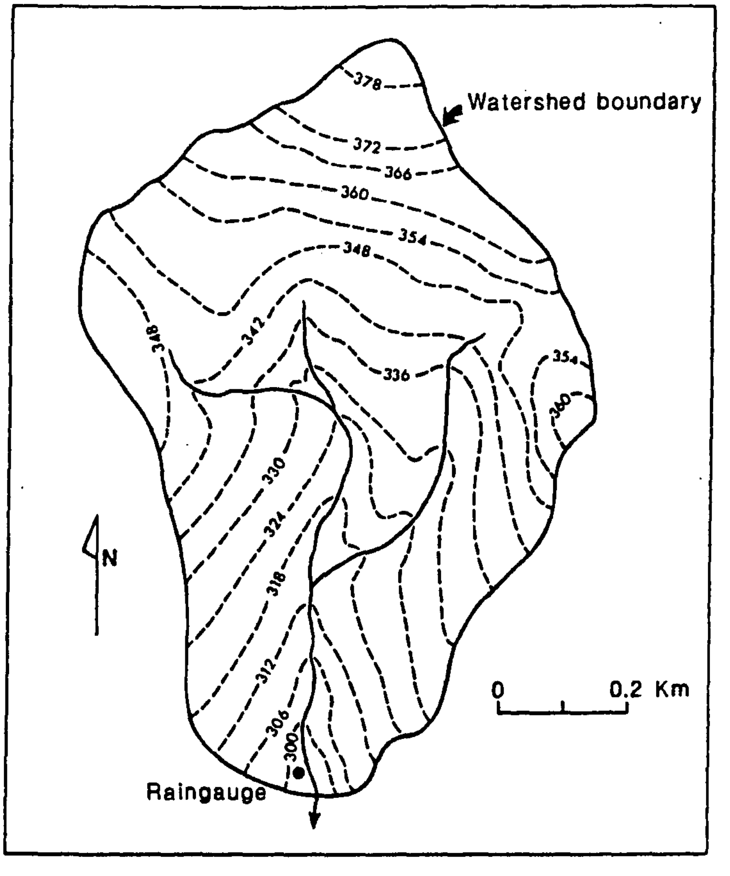


Figure 61 Watershed 2, unamed tributary of Sleepers River catchment, Connecticut River Basin, North Danville, Vermont

permanent and fed by a zone of saturation and seepage which occurs at the loess and till interface. Topographic maps of the four catchments are provided in figures 62, 63, 64, and 65. W-1 is located 9.65 km south west of Treynor. The catchment is laid to contour corn and exhibits high levels of fertility and good farming practices. W-2, also 9.65 km south west of Trynor, has similar characteristics to W-1 but is a tributary of another stream, the Keg Creek. W-3 is located 4.83 km south west of Treynor and contains pasture with controlled grazing. Finally, W-4, located 4.83 km south west of Treynor, contains contour corn on grassed backed slope terraces. All terraces in W-4 are as recommended by the ARS.

The five catchments which have been introduced here are all below 0.6 square km. Although these may be considered to be small, certain limitations are imposed upon the catchment scale by the nature of a three year research programme. Within a three year period, it is considered that three potential research strategies are feasible within a geographical hydrological modelling exercise.

Firstly, at one extreme, it would be possible to develop and implement an entirely new mathematical hydrological model. This would demand such an investment of time that evaluation and testing could only be undertaken for one catchment. Secondly, it would be possible to provide a modification to one component of a currently utilized hydrological model, thus allowing sufficient time for a more detailed evaluation of the modified model on a series of catchments exhibiting different characteristics. Thirdly, and at the other extreme, it would be possible to apply a currently used model to a very large number of catchments, but to provide no model development. In this third strategy, a broader and more comprehensive model evaluation could be accomplished.

The first strategy has been a very popular choice. Feldman et al (1984) stressed that emphasis has been placed upon model development whilst support, documentation, and evaluation have been neglected. This has led to a multiplicity of mostly underutilized models with no clear

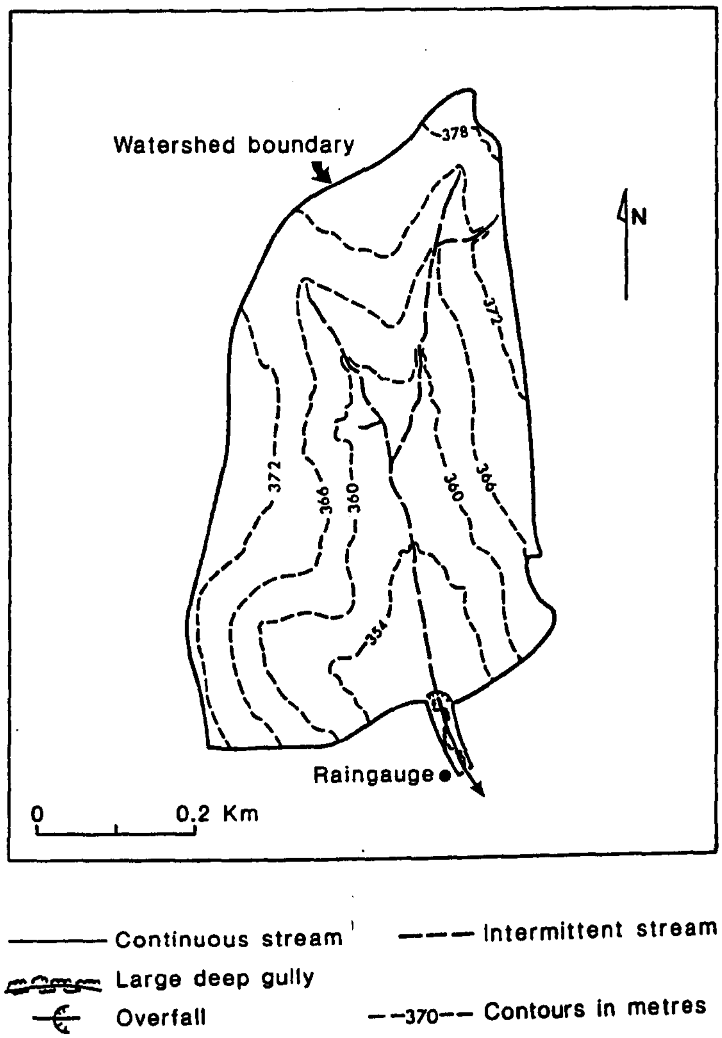


Figure 62 Watershed 1, Silver Creek, West Nishnabotna River, Missouri River Basin, Treynor, Iowa

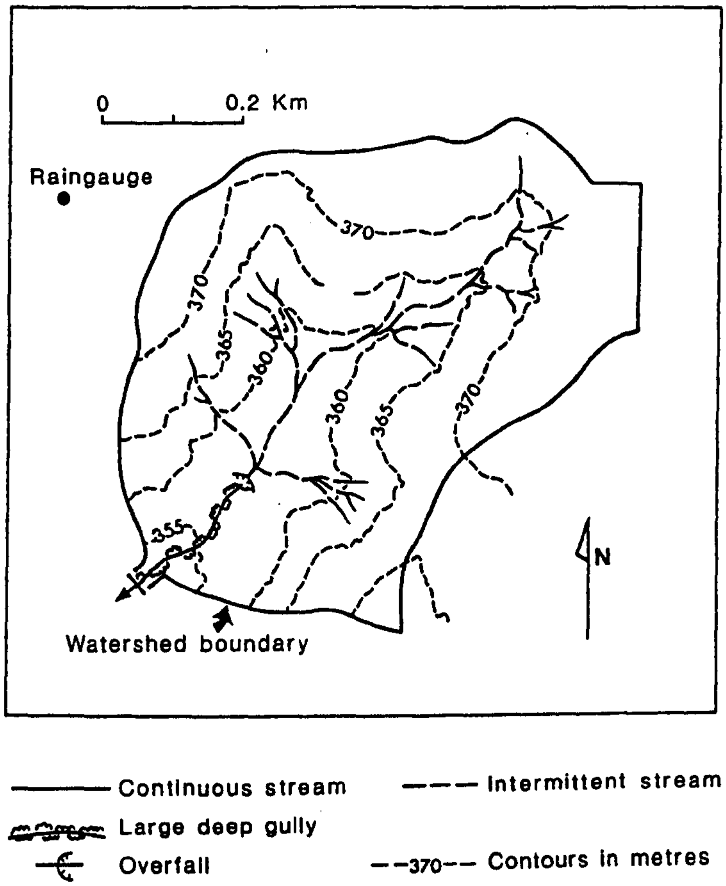


Figure 63 Watershed 2, Keg Creek, Missouri River Basin, Treynor, Iowa

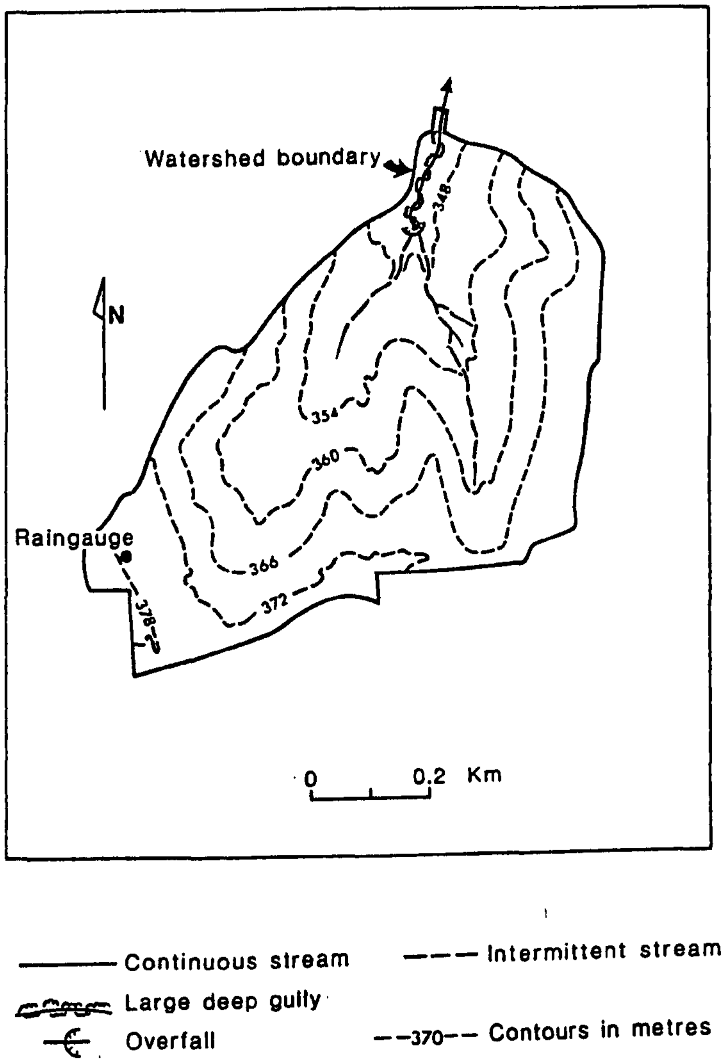


Figure 64 Watershed 3, Silver Creek, West Nishnabotna River, Missouri River Basin, Treynor, Iowa

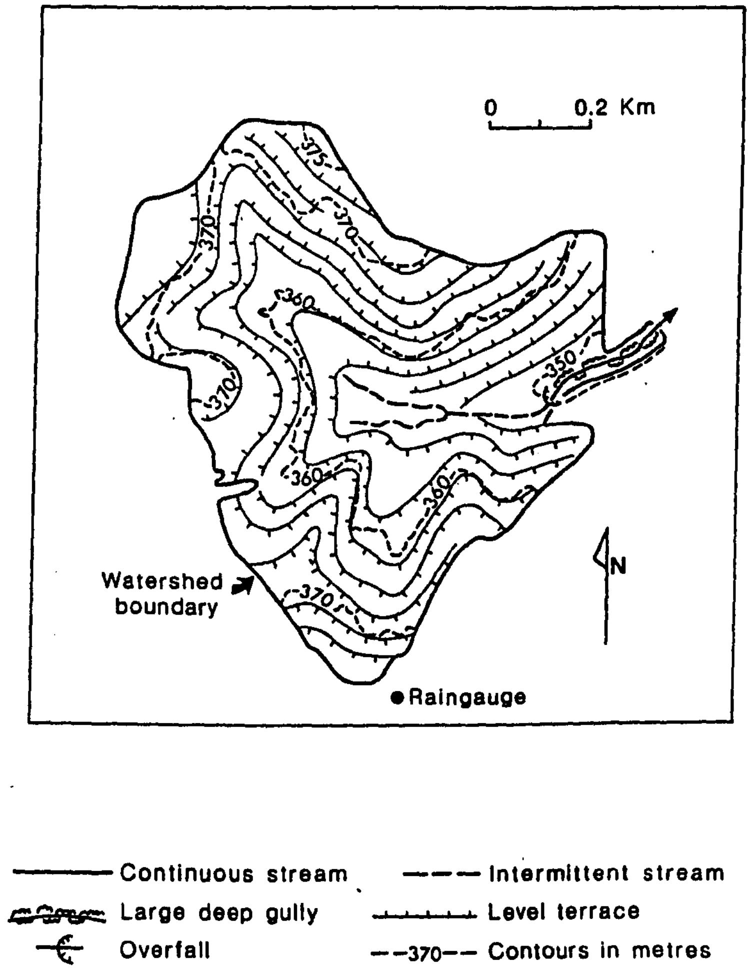


Figure 65 Watershed 4, Silver Creek, West Nishnabotna River, Missouri River Basin, Treynor, Iowa

recommendations for future requirements and research. Certainly during a three year research period, insufficient time would remain after model design and implementation fully to evaluate the model and to examine its full potential.

The third strategy has, in comparison, not commonly been undertaken. It has been stressed in section 1.3 that model evaluation has not been a popular occupation in mathematical hydrological modelling. However, although providing an opportunity for a comprehensive model evaluation and examination of operational applications, the third strategy would not allow for an investigation of ungauged catchment applications as no suitable model could be identified. It would also not allow for the examination of the potential of a physically based, rather than an empirical model for application purposes.

These issues were considered to be of importance and therefore the second strategy was adopted in this analysis. A modification to the infiltration component of HYMO was undertaken, and the period of model modification and implementation has necessarily limited the available time for catchment selection, data collection, and preparation. Thus seven small catchments were chosen. This provides a good compromise between the time limitations of a three year research programme and the need to evaluate the model over a range of catchment conditions.

The small size of catchments is not a disadvantage because the emphasis in this investigation of HYMO and HYMO2 has concentrated upon the hydrograph computation procedure. It has not been designed to examine the characteristics of the Variable Storage Coefficient channel routing technique. The selection of smaller catchments which can in the context of the application of HYMO2 be treated as single subcatchments, has allowed the hydrograph computation to be investigated without the complications of the incorporation of the routing procedure.

6.2 Parameter estimation procedure for HYMO2

The five catchments which have now been introduced in this chapter are all below 0.6 square km (table 32). No subdivision of catchments has been necessary, and consequently no channel cross section information is required for channel routing operations. The catchment characteristics: area, elevation difference, and main stream length (table 32), have been derived for all five catchments from maps of the scale and detail illustrated in figures 61 to 65. The determination of the soils data will now be discussed for each catchment.

There are five major soil types in the Watershed W-2, North Danville, Vermont. These include sandy loams, silt loams, and loams, and are namely, Colrain, Peacham, Calais, Cabot, and Woodstock. The details concerning soil horizon depths and soil textural characteristics of each layer were available from the USDA ARS descriptions of the catchment (table 33). The division of each soil horizon into cells was accomplished according to the general rule that cells in the top layer must not be greater than 0.1 metres and in the lower two layers, not greater than 0.15 metres. From the soil texture information, the Brakensiek and Rawls charts were used to define the soil hydrological characteristics. For all soil textures, the centroid position on the Bakensiek and Rawls charts was used. Detention capacity was assumed to be zero and a uniform initial relative saturation of 80% was assumed.

The four catchments near Treynor all contain the same four soil types, but each soil occupies different proportions of the total catchment area. The four soil types are Monona, Marshall, Napier, and Ida, and comprise silt loams and silty clay loams. Very little information was available on the layering characteristics of these soils and therefore, no layering of the representive soil columns was incorporated. The hydrological characteristics of each soil texture group were derived from the centroid position of the Brakensiek and Rawls charts. The soil column which is defined by the depth of the soil is divided into equal sized cells of 0.05 metres for Napier (the deepest soil) and 0.025

metres for the other three soils. The details of the soils in all four of these catchments are provided by table 33. The detention capacity of catchment W-4 was set at 0.01 metres. This value is estimated according to the terracing. No detention capacity was assumed for the other three catchments. Initial relative saturation was, in the absence of soil moisture information and based on previous experience, assumed to be 80% at the surface, and to increase uniformly with depth.

The precipitation data for all storms applied to these five catchments were converted into cumulative totals at equal time intervals, the form which is required by HYMO2. The measured hydrograph for each storm event was also input to HYMO2 for comparison. The storms which were used and the runoff which they produced are indicated in table 34.

Experience of application of the model to these five catchments, and those of Texas and Arkansas, has illustrated that in order to provide the data for model application, the user is involved in four stages. Figure 66 illustrates these stages, which include data collection, data preparation, data entry and data checking.

Data collection

This involves securing three sources of information: a topography map of the catchment, a soils map and accompanying description, and precipitation data. Depending upon the level of information which is available, the precipitation data might be in the form of recording rain gauge data, storm totals or predicted rainfall data. The distribution of precipitation, where only storm totals are available, may be provided by application of one of the standard Soil Conservation Service rainfall distribution models.

Data preparation

This involves the user in a number of decisions as to the manner in which the catchment should be characterized, the use of the Brakensiek and Rawls tables and charts to derive soil hydrological properties, and a series of manual calculations to convert precipitation data into the form required by HYMO2. All of these actions could potentially

Table 33: Soils information for application of the infiltration model to the five catchments in Vermont and Iowa

Soil type	USDA soil texture	Average depth of soil (metres)	Catchment area (%)			
W-2 North Danville, Vermont						
Colrain	sandy loam	0.84	41			
Peacham	silt loam	0.31	5			
Calais	loam	0.69	9			
Cabot	silt loam	0.46	13			
Woodstock	sandy loam	0.61	32			
Treynor, Iowa			W-1	W-2	W-3	W-4
Monona	silt loam	0.15	38	24	50	48
Marshall	silty clay loam	0.254	35	36	22	23
Napier	silt loam	0.762	16	17	22	23
Ida	silt loam	0.076	11	23	6	6

Table 34: Storm characteristics for the five catchments in Vermont and Iowa.

Storm number	Date of storm start (d.m.yr)	Time of storm start (hrs)	Time increment of rainfall (hrs)	Storm duration (hrs)	Total precip-itation (mm)	Total runoff (mm)
W-2, North Danville, Vermont						
1	11.9.1968	06:00	1.0	16.0	38.1	0.36
2	21.7.1969	15.30	0.25	3.25	24.1	0.31
3	28.8.1970	14:45	0.25	6.5	37.3	0.54
4	16.7.1967	04:30	0.5	9.0	43.9	4.67
5	30.7.1960	12:00	1.0	11.0	43.9	2.72
6	2.6.1961	02:00	0.25	6.0	21.1	4.39
W-1, Treynor, Iowa						
1	2.8.1970	21:40	0.1	1.8	67.1	22.96
2	26.6.1966	02:32	0.1	1.0	22.9	9.27
3	14.6.1967	05:10	0.1	1.7	19.6	12.34
4	20.6.1967	20:56	0.05	2.9	156.0	107.30
5	7.6.1967	17:05	0.1	1.4	41.9	31.3
W-2, Treynor, Iowa						
1	2.8.1970	21:37	0.1	1.8	41.9	17.96
2	26.6.1966	02:26	0.1	1.2	22.9	10.19
3	14.6.1967	05:13	0.1	1.7	19.8	10.97
4	20.6.1967	20:56	0.05	2.75	143.0	96.16
5	7.6.1967	17:10	0.1	1.0	43.2	25.62
W-3, Treynor, Iowa						
1	2.8.1970	21:33	0.1	1.7	41.7	1.52
2	25.6.1966	23:05	0.1	1.3	28.7	4.14
3	14.6.1967	05:10	0.1	1.8	21.1	2.99
4	20.6.1967	20:52	0.1	2.8	98.6	33.75
5	7.6.1967	17:10	0.1	1.3	23.9	4.17
W-4, Treynor, Iowa						
1	2.8.1970	21:33	0.1	1.7	41.7	0.15
2	26.6.1966	23:05	0.1	1.3	28.7	1.27
3	14.6.1967	05:10	0.1	1.8	21.1	1.21
4	20.6.1967	20:52	0.1	2.8	98.6	9.53
5	7.6.1967	17:10	0.1	1.3	23.9	1.44

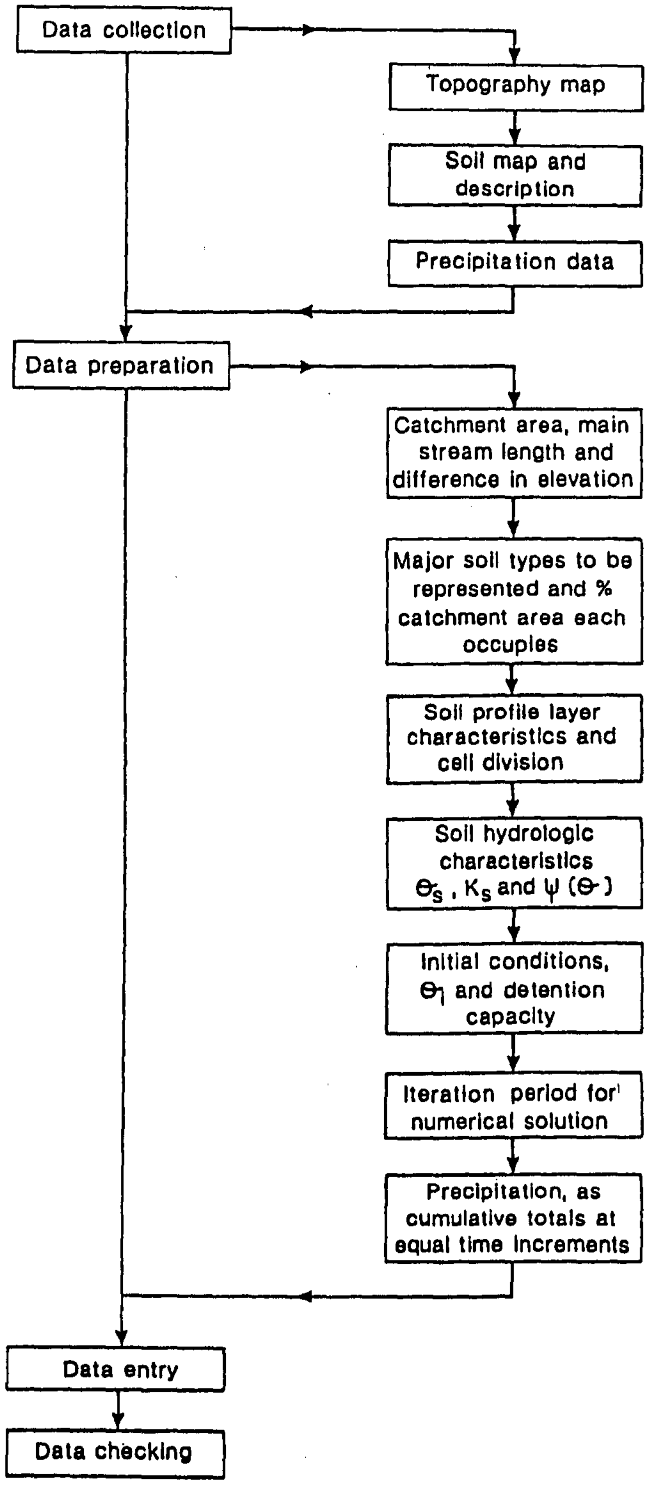


Figure 66 The four stages in data generation

introduce error into the predictions. To reduce this source of error, and to operationalize the model as fully as possible for the nonprofessional hydrologist, it is important that an attempt should be made to computerize certain procedures in this data preparation stage.

It is necessary that the catchment characteristics required by the unit hydrograph method: catchment area, main stream length, and difference in elevation, be determined by the user. This is a straightforward, but tedious procedure, which does not require specialized skills. The determination of area could only be computerized should a digitizing facility be available on the computer system. Access to this cannot be assumed for the microcomputer system user. However, it is important to stress to the user the importance of accuracy in the specification of these three catchment characteristics. Figure 67 provides a summary of certain results of the application of a deterministic sensitivity analysis to the unit hydrograph method which is used by HYMO2. The sensitivity of the peak unit discharge to the three catchment characteristics is illustrated. For a constant elevation difference of 15.24 metres, figure 67(A) illustrates that as the area of the catchment increases, i.e. topography becomes less steep, the sensitivity of unit peak to length of main channel increases. For any given area and height combination, the sensitivity to length of main channel is greatest when the channel is shorter. Figure 67(B) illustrates that the unit peak is sensitive to catchment area. This sensitivity is greatest for smaller catchment areas and varies quite significantly according to the height to length ratio. As this ratio decreases and topography becomes less steep, then sensitivity to area decreases. Figure 67(C) illustrates that the sensitivity of the model to elevation difference decreases as the height difference increases. The magnitude of this sensitivity is related to the catchment shape, being less for narrower and elongated catchments. It is important therefore, that these three catchment characteristics are specified as accurately as possible.

The selection of the major soil types is another choice for which very little direct help can be provided specifically for the catchment of interest to the user. Examination of the soils map is necessary to

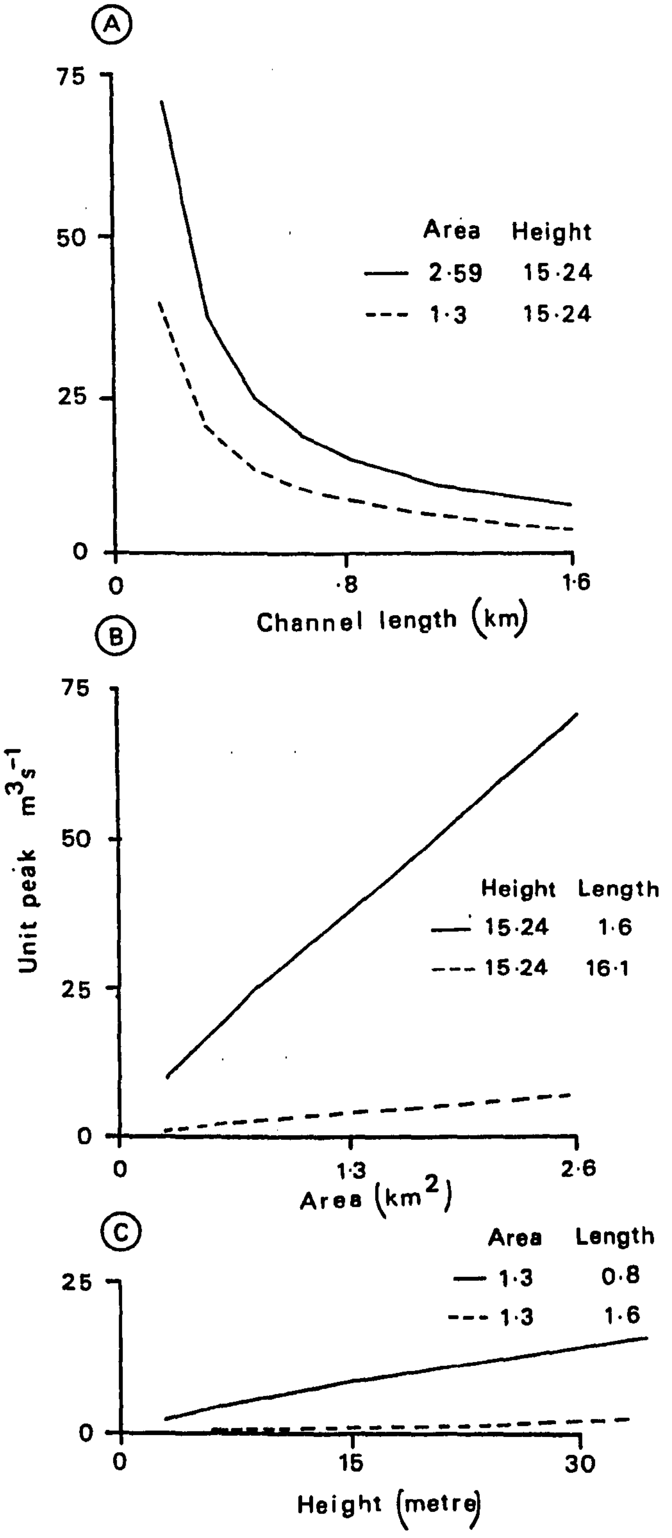


Figure 67 Sensitivity of the unit hydrograph procedure to (A) channel length (B) catchment area (C) elevation difference

identify the major soil types, and to determine the percentage of the catchment area which each occupies.

It is intended that the experience of a series of applications of HYMO2, which have been documented in this thesis, will be useful in defining a very general series of guidelines to which the user may refer when selecting the appropriate number of soil columns to represent the catchment area, the layering characteristics of each soil column, and the dimensions of the cells in the soil column.

The number of soil columns will reflect a trade-off between a possible increase in prediction accuracy and the increased computer and data preparation costs which are associated with the application of a large number of soil columns. If sufficient detail is available in the soil map descriptions to define the soil texture characteristic of up to three layers in the soil, then this information can be used. Should this degree of data not be available, the user must have access to advice or a standard procedure which can be applied. Choice of the size and hence the number of cells in the soil column should also be based on the past experience of application of the model.

If a general series of rules based upon the results of gauged applications on the model can indeed be established, then it is important that a user does have access to this information. There are two forms in which this information may be stored. Firstly, it can be provided in a manual which accompanies the computer program, or secondly, it can be provided on-line. The information can be held in the computer program and provided to the user on request, in an interactive form, as the user enters the data for model application. For example, where the user is required to specify the number of soil columns for the catchment area, if insufficient information is available, or if the user is unfamiliar with the model, then the user may interrogate the system for advice. Based on past application, the number of soil columns can be related to catchment size, precipitation characteristics, the size of the computer system, and to any constraints which the user might be placing on response time. The user will then be in a position to operate the model to a greater advantage and based upon the past experience of the model application, rather than on past personal experience. With time, the information which is held by the system can be increased.

The use of the Brakensiek and Rawls charts to provide the soil hydrological characteristics, saturated hydraulic conductivity, saturated moisture content, and soil moisture characteristic curve, is one very obvious area where operator error may be reduced. The look-up procedure which uses the tables could be replaced by a series of expressions which are more easily computerized. It is only necessary for the user to define the soil texture class, sand or loam for example, for each soil type, and each layer where appropriate. This information is then entered into a program which will firstly convert the soil texture category to a percentage clay and percentage sand figure, secondly, it will determine the corresponding numerical values for these three soil hydrological parameters. The values are then automatically stored in the form required by the infiltration program thus reducing the amount of data entry required of the user. The program to generate the values of saturated hydraulic conductivity and saturated soil moisture content has been developed by the SCS at Beltsville, Maryland. To derive the saturated hydraulic conductivity for example, in inches per hour, the following expression is used:

$$K_S = e^{\begin{array}{l}[-8.9685-0.0282(cl)+19.5235(POR)+0.0001(sd)^2-0.0094(cl)^2 \\ -8.3952(POR)^2+0.0777(sd)(POR)-0.0029(sd)^2(POR)^2 \\ -0.0195(cl)^2(POR)^2-0.00002(sd)^2(cl)-0.0273(cl)^2(POR) \\ -0.0014(sd)^2(POR)-0.000003(cl)^2(sd)]\end{array}} \quad (67)$$

Where:

cl - percentage clay
sd - percentage sand
POR - porosity

The initial moisture content, detention capacity and iteration period must be specified by the user. Again, from repeated application of the model, a series of general rules will be derived and then rather than specifying the exact numerical figures for these parameters, the user could, by supplying a more general level of information, rely on the data preparation routines in the model to derive the data which, on the basis of past experience, are considered to be most appropriate.

Similarly, the precipitation data can be converted to the format which is required by HYMO2, from the form in which they are available.

Data entry

Under the proposed scheme, the amount of data entry required by the user is reduced. All numerical values which are generated by the data preparation procedures are automatically produced in the form required by the model.

Data checking

It is necessary to check the data before model execution is initiated. A certain degree of data checking can also be incorporated into the program, and checks on units, and on missing or incorrectly typed data will certainly be very effective.

Figure 68 illustrates the nature of the program which is suggested here. This figure illustrates the information which is required to operate the hydrograph computation. It will be recalled that this hydrological procedure comprises three sections: the derivation of the unit hydrograph, the derivation of incremental runoff, and the convolution of these two series to produce the catchment outflow hydrograph. Figure 68 indicates the information which must be supplied by the user and the two stages of data preparation and checking which could be undertaken by the computer program, before model execution begins. Certainly as further enhancements to the program are developed, a hierarchy of paths through the data preparation, entry and checking stages could be provided depending upon the nature of the catchment data available, and the status of the operator. Further refinement could involve the

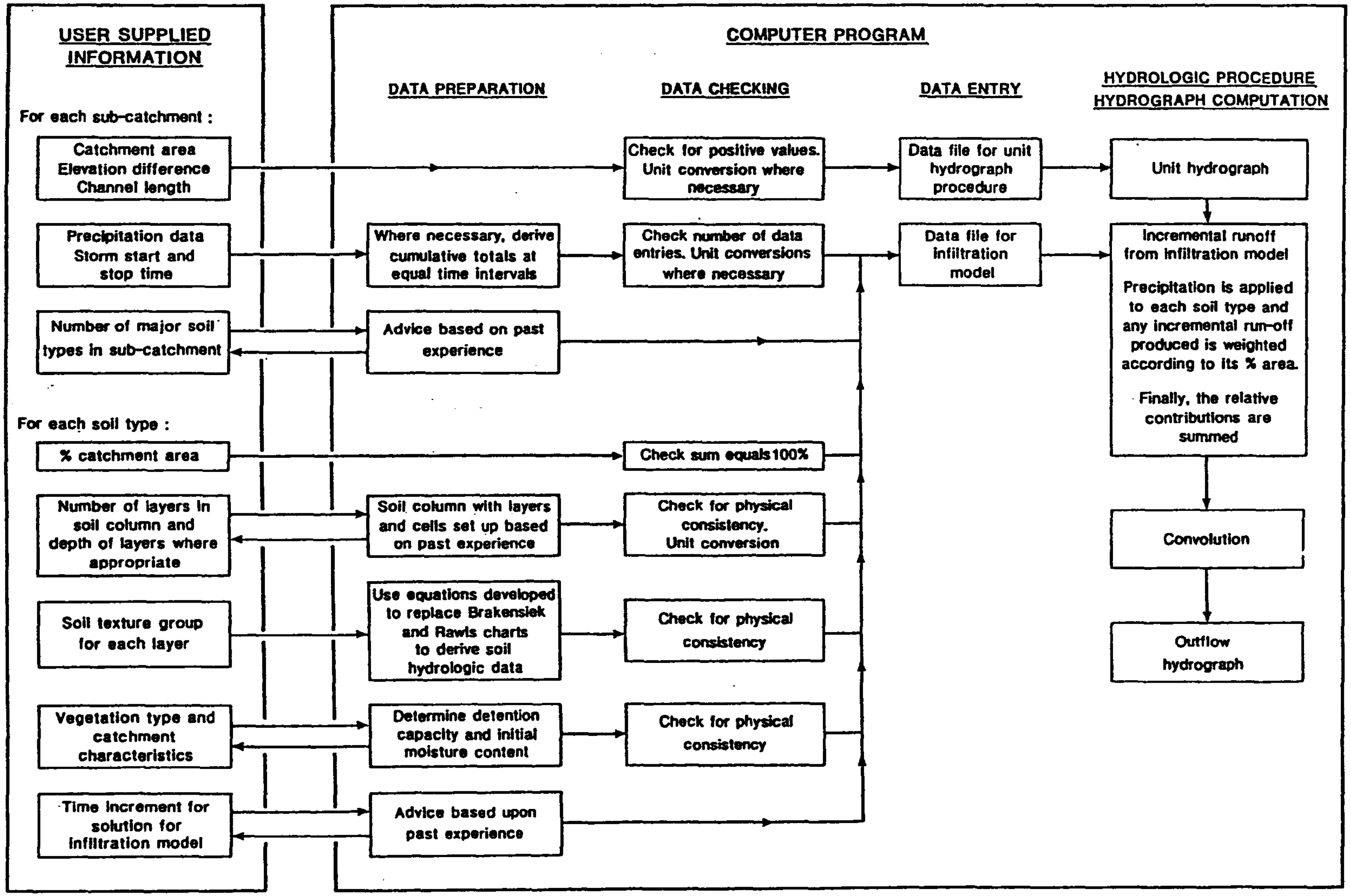


Figure 68   Proposed operational version of the hydrograph computation in HYMO2

incorporation of editing facilities, and the capability to view and to check data both in graphical and tabular form.

6.3 Comparison of calculated and measured hydrographs

In this series of applications of HYMO2 to catchments in Vermont and Iowa, it is not proposed that any fine tuning of the model parameters be undertaken to assure the closest fit to the measured hydrograph which is possible. Rather, the catchment data which have been derived are to be used in one application to each storm. Hence, the catchment is treated as if it were ungauged.

To assess the accuracy of the model predictions for this wide range of experimental frames, the same two stage procedure of evaluation will be followed as that suggested and adopted in chapter 5, and figure 41.

In total, 26 experimental frames (six storms applied to W-2, North Danville, Vermont and five storms to each of the four catchments in Treynor, Iowa) have been described here. Not all of these will be reported in detail during the following discussion. A number of selected examples will serve to illustrate the major points which can be made. To identify each experimental frame, the catchment name and the storm number, indicated in table 34, will be provided.

The two stage procedure which compares the calculated and measured hydrographs (figure 41) will be followed in the same order as in the comparison of the predicted hydrograhs for the North Creek and Sixmile Creek.

Stage 1: <u>Comparison of calculated and predicted hydrograph</u>

A comparison of calculated and measured hydrographs for a selection of experimental frames is provided by figures 69 to 73. The change in scales between the North Danville and four Treynor catchments should be noted. The predictions provided by HYMO2 for W-2, North Danville do not approximate the measured to any great degree, although the large vertical scale for these time series should be appreciated. The three storm events illustrated in figure 69 represent the range of inaccurate and inconsistent results which are obtained for this catchment. For storm 3, (figure 69(A)) the predicted hydrograph bears no similarity in form or timing to the measured. Peak discharge is also highly overestimated. The measured hydrograph for storm 4 (figure 69(B)) displays a double peak. The calculated hydrograph also has a double peak but neither the timing nor the relative magnitudes of the two peaks are correct. For storm 6 (figure 69(C)), the model predicts a much lower runoff than was experienced in the catchment.

HYMO2 provides underpredictions of peak discharge for all 10 storms applied to W-1 and W-2, Treynor, and figures 70 and 71 provide four examples of this. The relationship of calculated and measured hydrographs in these figures is very similar in form for those derived for the North Creek and Sixmile Creek. HYMO2 has a tendency to overpredict discharge during the very early stages of the hydrograph rise, then to underpredict discharge during the peak and finally to overpredict discharge during the latter phases of recession. With the exception of storm 5 applied to W-1 however (figure 70(B)), the timing of the predicted hydrograph quite closely approximates the measured.

Figure 72 provides the calculated and measued hydrographs for storm numbers 3 and 4 applied to W-3 Treynor, Iowa. The response to storm 3 (figure 72(A)) is typical also of storms 1, 2 and 5 applied to this catchment. The measured hydrograph response is delayed and the model does not predict this. The overall hydrograph form and runoff volume are similar, but the timing is poor. The prediction for storm 4 (figure 72(B)) however is encouraging. The runoff volume and timing are very well predicted, but as noted above, the peaked form of the measured hydrograph is not predicted by HYMO2. Figure 73 illustrates the overprediction made by HYMO2 for storm 4 on W-4 Treynor, Iowa (figure 73(A)). The predicted response to storm 5 (figure 73(B)) again has a

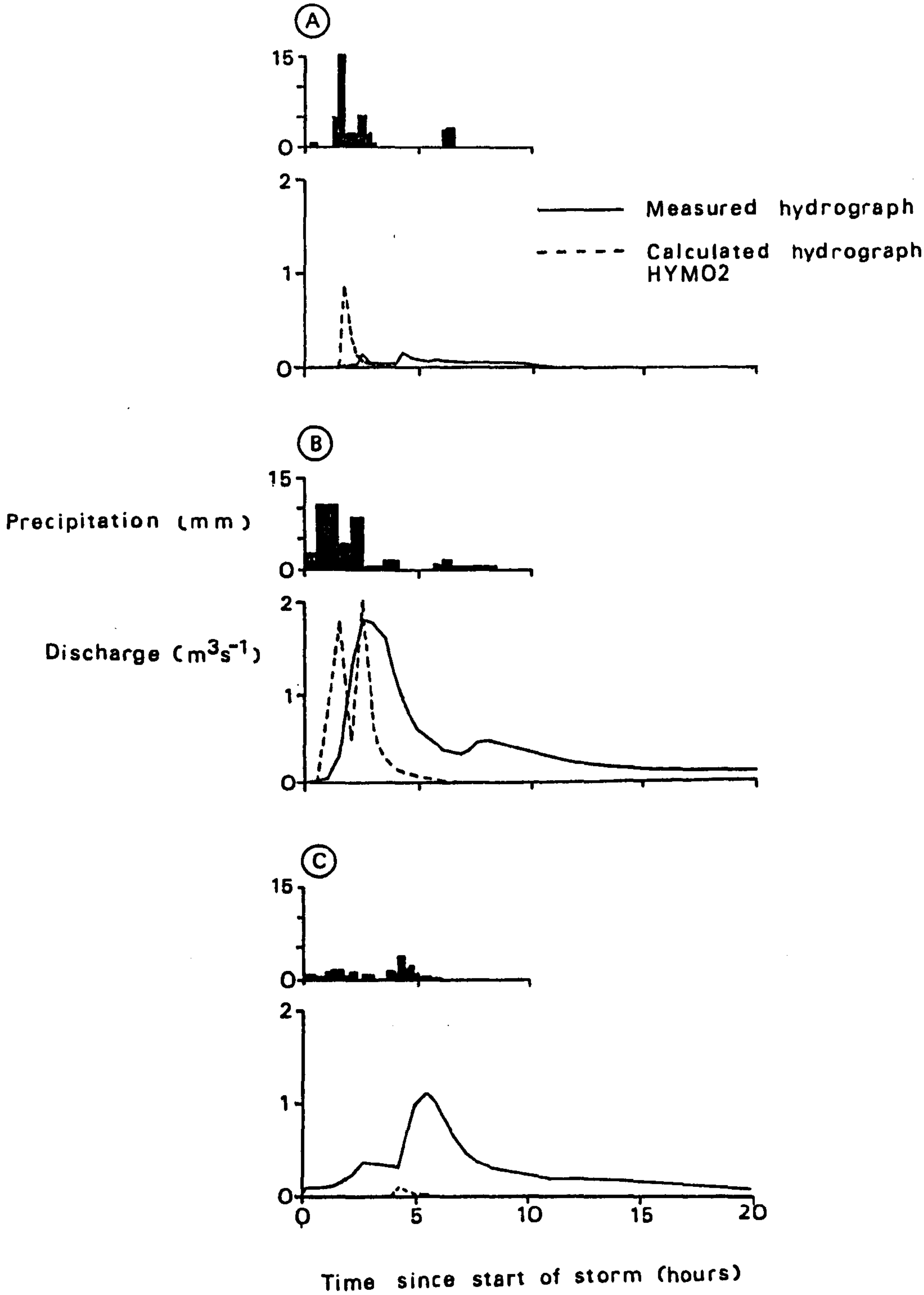
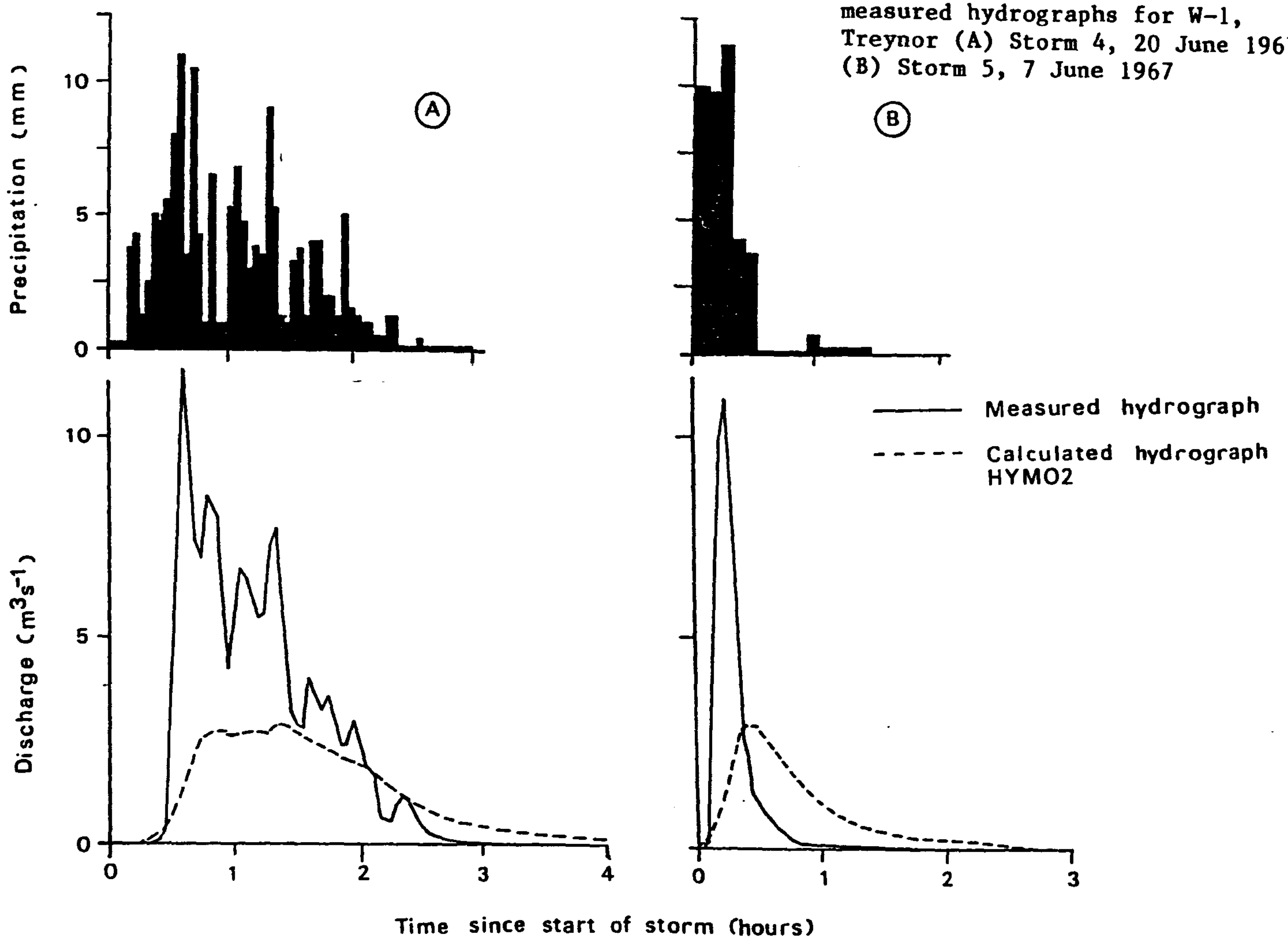


Figure 69 Comparison of calculated and measured hydrographs for W-2, North Danville, Vermont (A) Storm 3, 28 August 1970 (B) Storm 4, 16 July 1967 (C) Storm 6, 2 June 1961

Figure 70 Comparsion of calculated and measured hydrographs for W-1, Treynor (A) Storm 4, 20 June 1967 (B) Storm 5, 7 June 1967



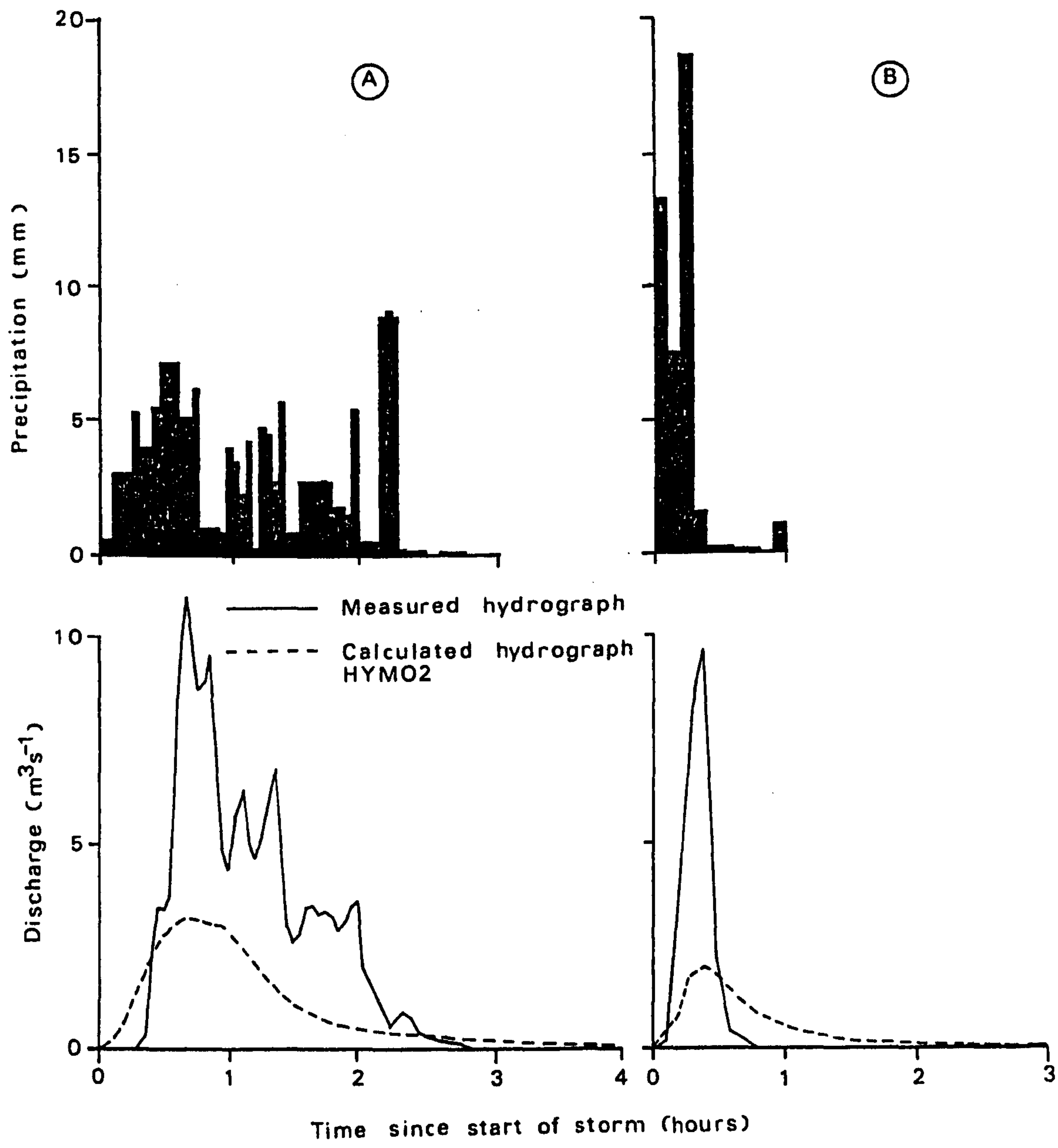


Figure 71 Comparison of calculated and measured hydrographs for W-2, Treynor, Iowa (A) Storm 4, 20 June 1967 (B) Storm 5, 7 June 1967

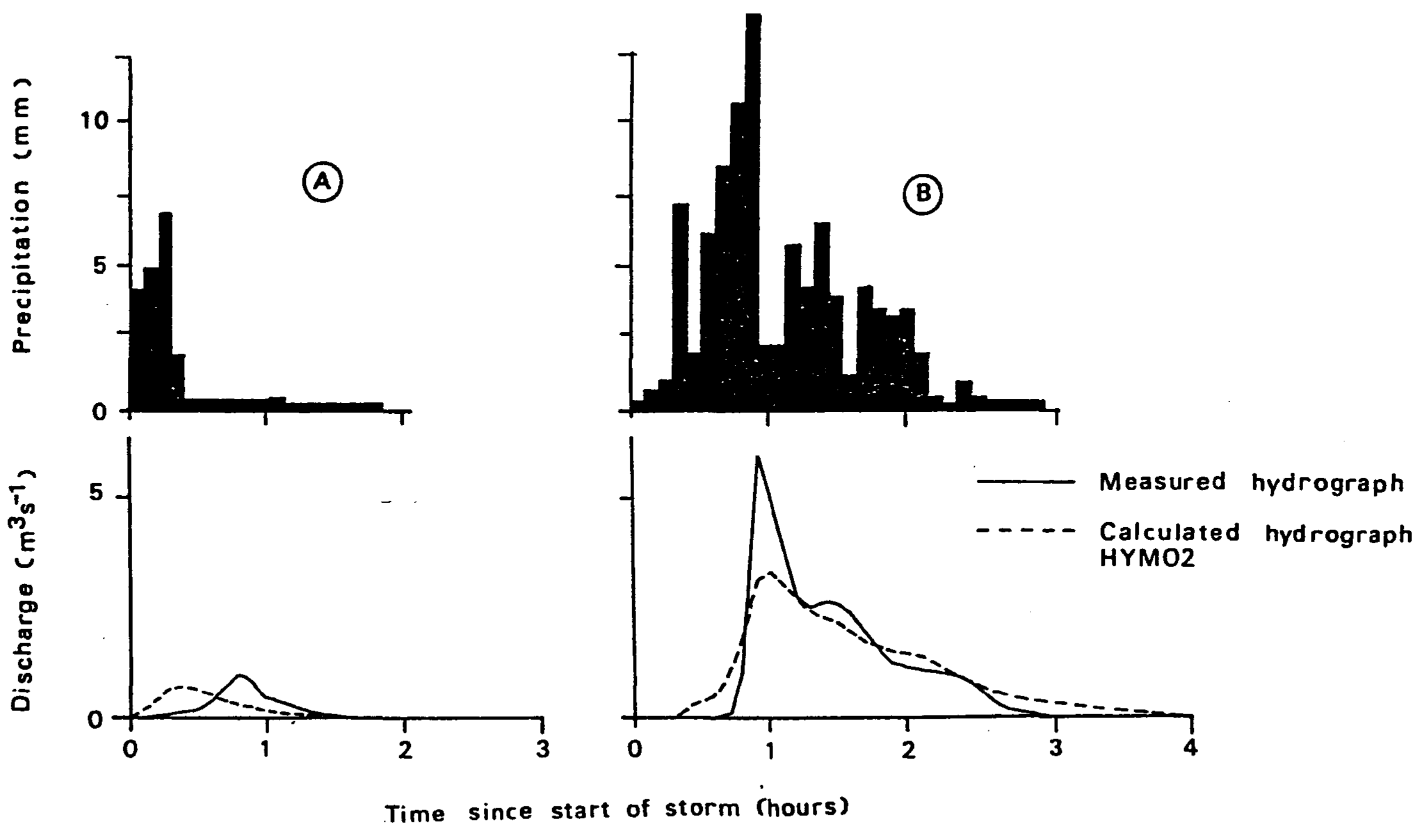


Figure 72 Comparison of calculated and measured hydrographs for W-3, Treynor, Iowa (A) Storm 4, 20 June 1967 (B) Storm 5, 7 June 1967

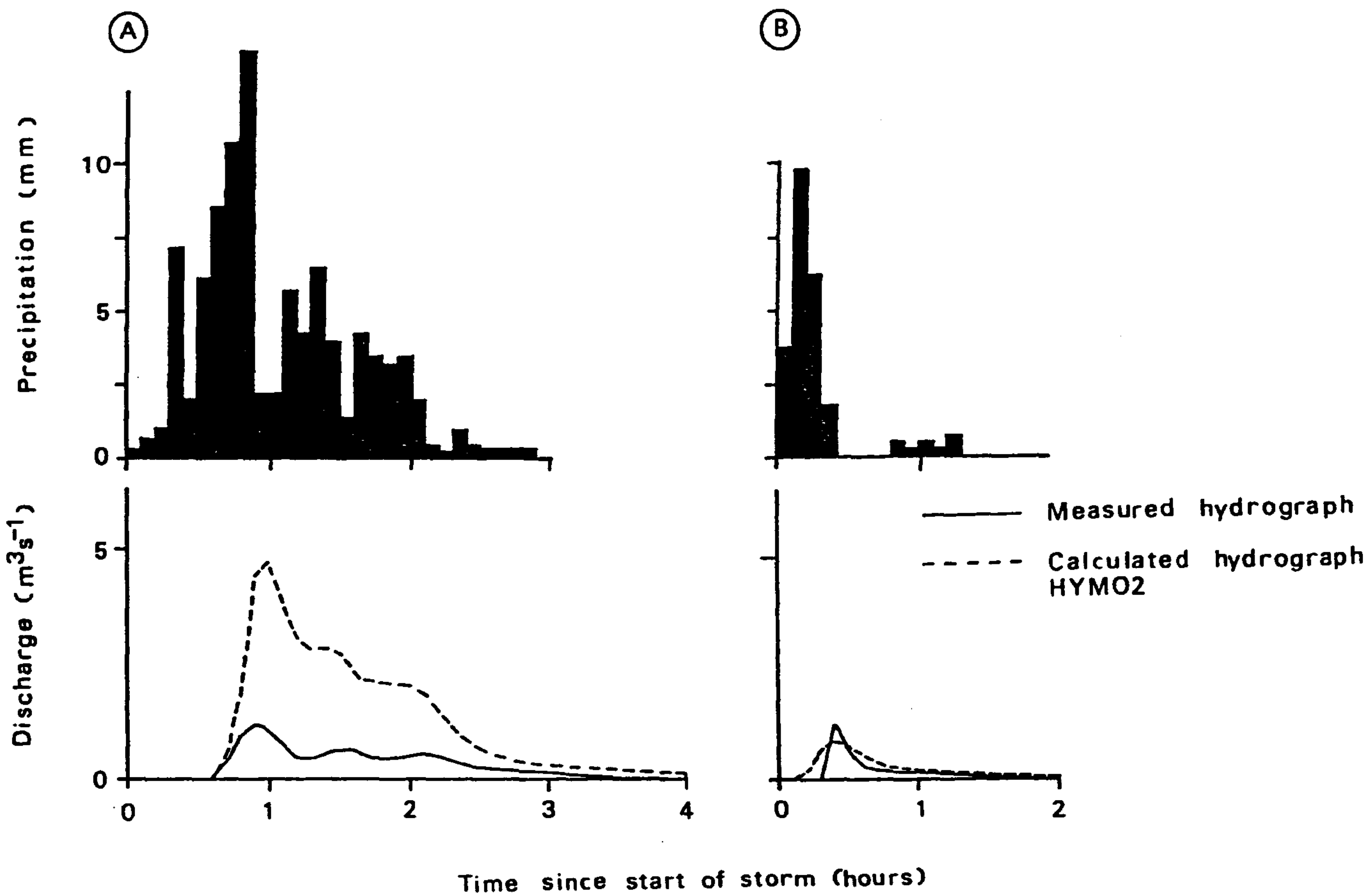


Figure 73 Comparison of calculated and measured hydrographs for W-4, Treynor, Iowa (A) Storm 4, 20 June 1967 (B) Storm 5, 7 June 1967

similar relationship to the measured as has been noted for the North Creek and Sixmile Creek.

A series of plots of calculated against measured discharge are provided by figures 74 and 75. The dashed line indicates the position of perfect prediction and the arrows indicate the order of occurrence of errors from t=0 and at successive time intervals through the storm event. Figure 74 illustrates quite clearly the range of overprediction (storm 3, figure 74(A))) to underprediction (storm 6, figure 74(B)) derived for this catchment. There is no systematic relationship between measured and calculated discharge for this catchment. The patterns of hydrograph prediction illustrated in figure 75(A) for storm 5, W-1 and in figure 75(B) for storm 5, W-2, Treynor, Iowa are typical of the response to the other storms applied to these catchments, and are also similar in form to those produced for North Creek and Sixmile Creek (figure 47). A systematic source of error appears to occur over a range of catchments which causes the hydrograph rising limb, peak discharge, and beginning of recession to be underpredicted, but for the discharges occurring during the latter stages of recession to be overpredicted.

A different form of hydrograph predictions is illustrated for storm 3 applied to W-3 Treynor, Iowa in figure 75(C). Here, the pattern is reversed, overpredictions of the rising limb and underpredictions of the falling limb occur. The predicted hydrograph is also illustrated to be out of phase with the calculated; two points in the curve, in the north and east corners, are observed rather than the more usual one, in the north east position. Finally, storm 5 applied to W-4 (figure 75(D)) displays a similar pattern to the Sixmile Creek and North Creek where overprediction of the rising and falling limb and underprediction of the peak discharge have produced a hydrograph which is very similar in terms of runoff volume, but not as peaked as the measured.

A comparison of percentage time to peak discharge error, percentage peak discharge error, and percentage mean discharge error for all 26 experimental frames is provided in figure 76. Percentage time to peak discharge error ranges much less widely than the other two indicies.

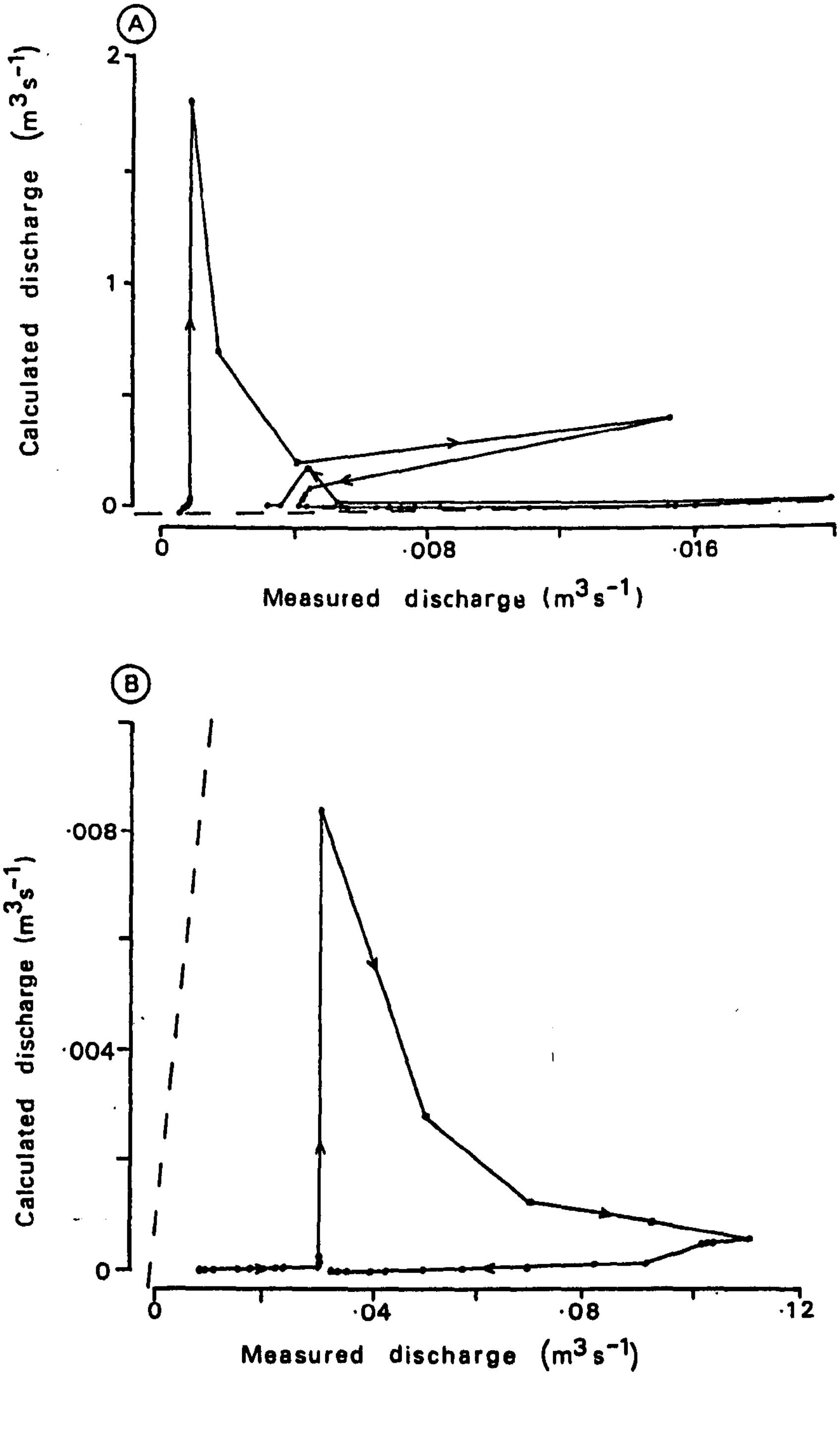


Figure 74 Relationship between discharge predicted by HYMO2 and measured discharge for W-2, North Danville, Vermont (A) Storm 3, 28 August 1970 (B) Storm 6, 2 June 1961

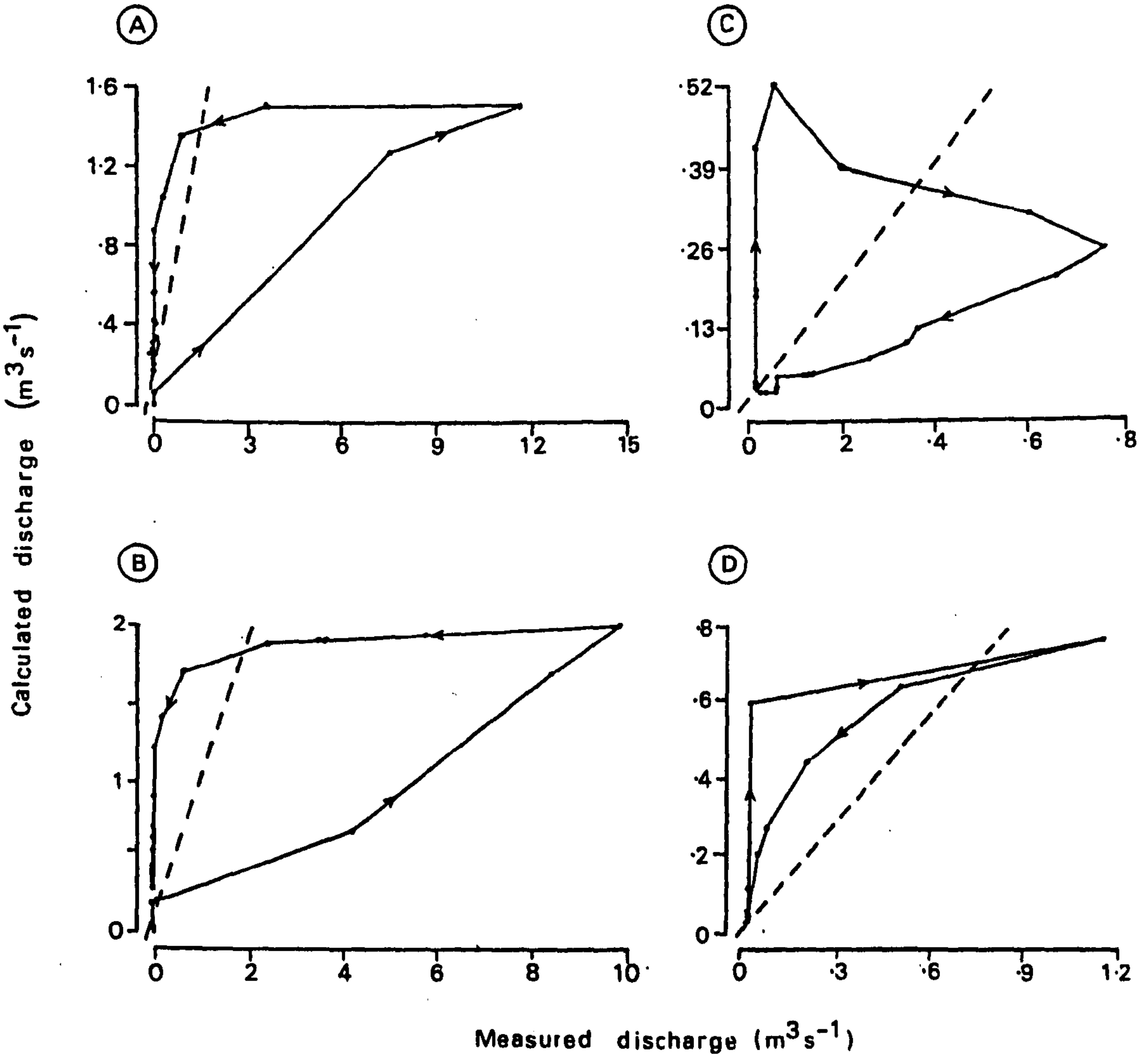


Figure 75 Relationship between discharge predicted by HYMO2 and measured discharge (A) Storm 5, 7 June 1967, W-1, Treynor, (B) Storm 5, 7 June 1967, W-2, Treynor (C) Storm 3, 14 June 1967, W-3, Treynor (D) Storm 5, 7 June 1967, W-4, Treynor

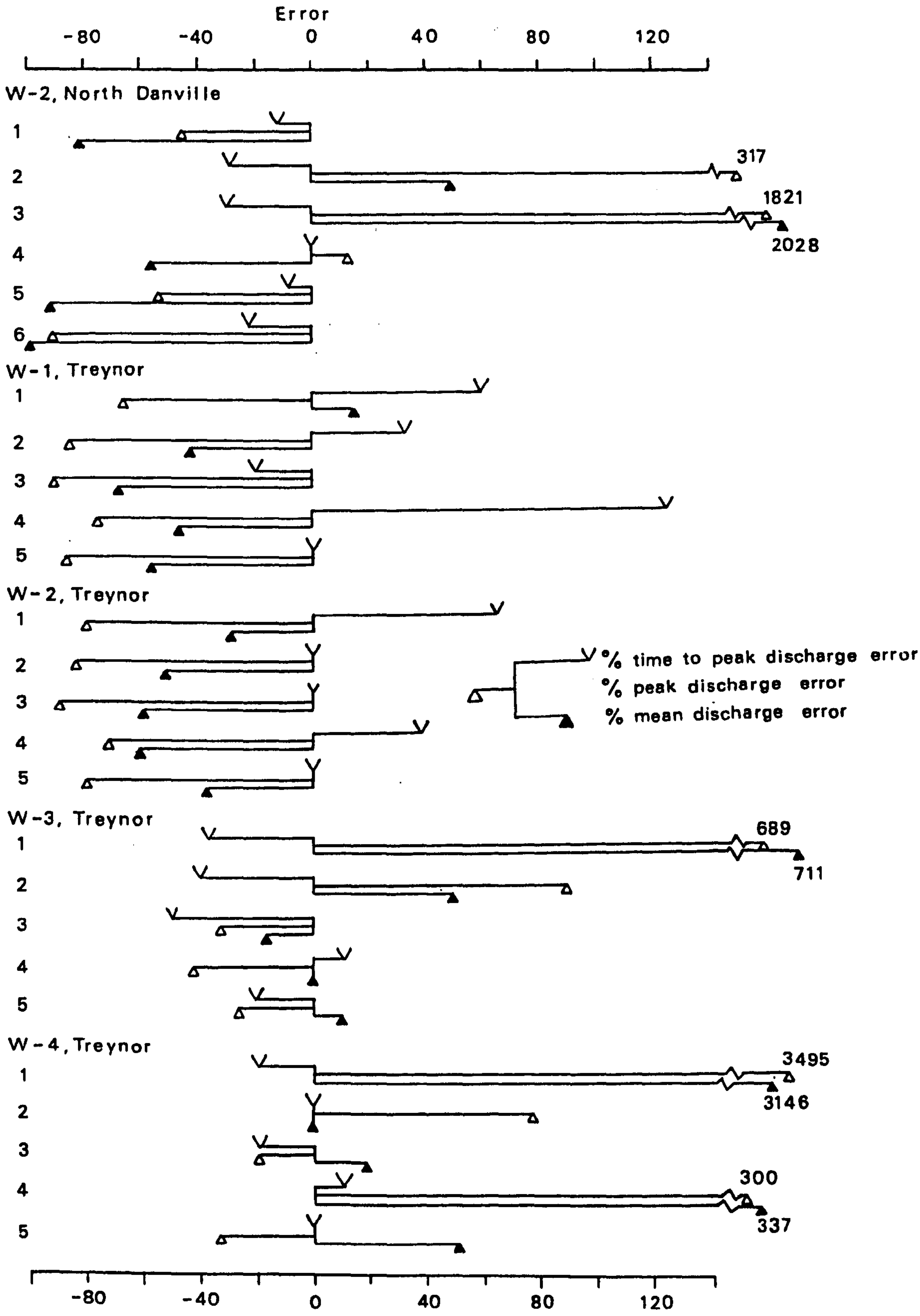


Figure 76 Percentage peak discharge error, percentage mean discharge error, and percentage time to peak discharge error for all 26 experimental frames

For W-2, North Danville, time to peak discharge is predicted exactly for storm 4 and underpredicted for the other five storms by between 9% and 30%. For both W-1 and W-2, Treynor, the exact time to peak discharge is predicted for storms 2, 3, and 4. Storms 1 and 5 are overpredicted for both catchments by between 9% and 125%. For W-3 and W-4, percentage time to peak discharge error ranges from -50% to +11% and -43% to +11% respectively. Over all 26 experimental frames, the time to peak discharge of 13 storms are predicted to within plus or minus 10% (including 9 exactly) and only in 4 cases of the 26, is the prediction of this hydrograph characteristic in error by greater than 50%.

Error associated with peak discharge is greater than that for time to peak discharge. For W-2, North Danville, the error ranges from -82% to +1882% and is for only one storm within 20% of the measured. For W-1 and W-2, Treynor, peak discharge is underestimated without exception by between 91% and 67%. For W-3, error ranges from -43% to +689%. However, the greatest range of error, -33% to +3498%, is experienced by W-4. Over all 26 experimental frames, there are no events where peak discharge is predicted to within 10%. In fact, in 19 of the 26 cases, errors of greater than 50% occur.

The error associated with the prediction of mean discharge is for most storm events slightly less than that associated with peak discharge. Very wide ranges are displayed for predictions made for W-2, North Danville, and W-3 and W-4, Treynor. Over all 26 experimental frames, the mean discharge of three storm events are predicted to within 10% (including two exactly) and 14 events are associated with error of greater than 50%.

The correlation coefficients and error standard deviations calculated for these 26 experimental frames are illustrated in figure 77. The correlation coefficients are very low and indicate very little association between the calculated and measured hydrographs. For 8 of the 26 cases, a correlation coefficient of between 0.5 and -0.2 exists, and 5 of these 8 occur for W-2, North Danville. Overall, for no storm is a correlation coefficient of greater than 0.9 found. The error

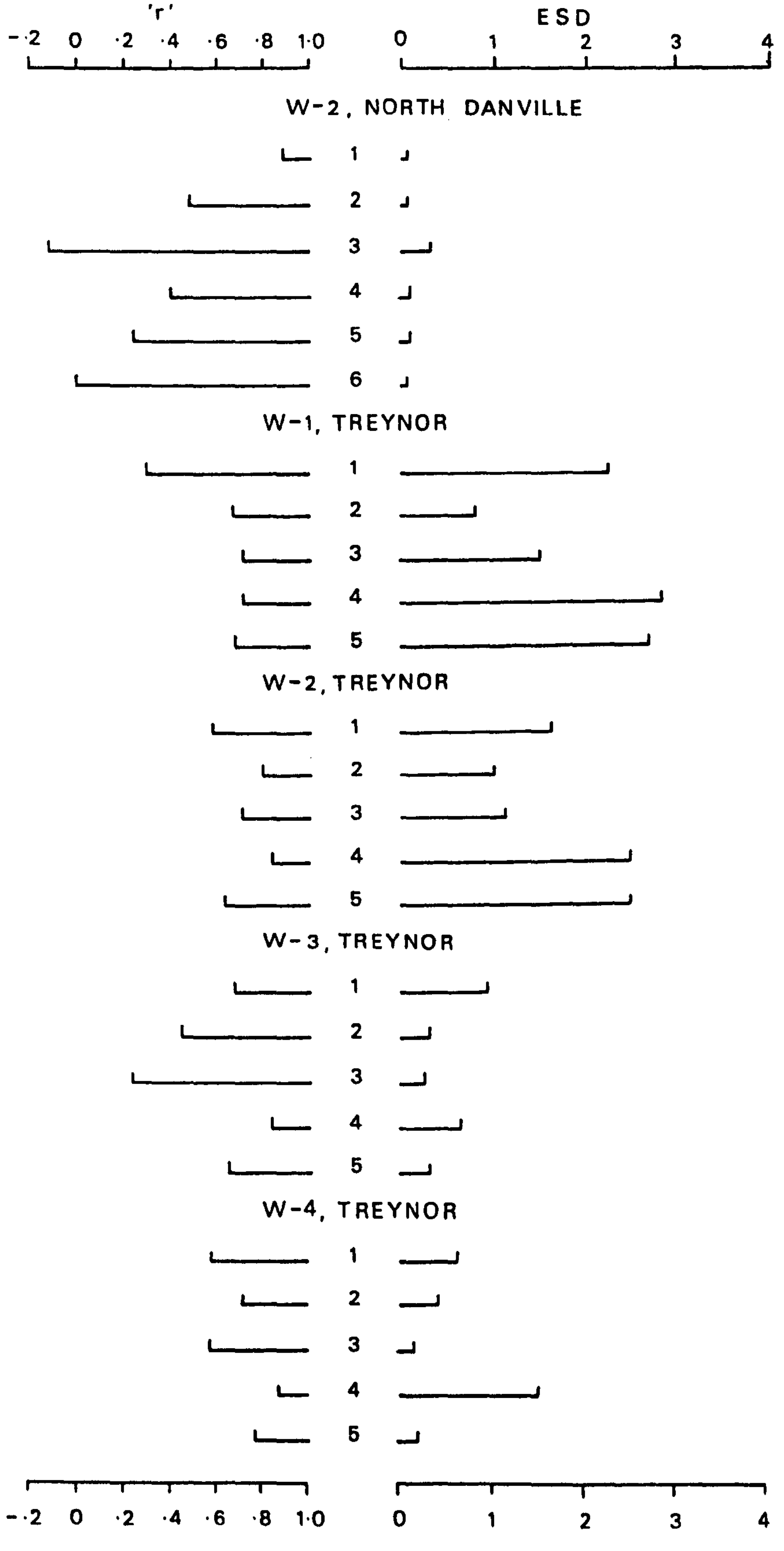


Figure 77 Correlation coefficient (r) and error standard deviation (ESD) for all 26 experimental frames

standard deviation values indicate a misleading picture of better predictions for the W-2 catchment, North Danville. The calculations of this statistic are affected by the absolute magnitude of the discharges involved, and which for this catchment are indeed very small. For the Treynor catchments however the error standard deviations are still low in comparison to the North Creek and Sixmile Creek, a maximum of 2.7 being displayed.

Stage 2: Evaluation of errors

Time series plots of model forecast error (measured discharge minus calculated for each time interval) for a selected number of storms are provided in figures 78 and 79, for each catchment. The differences in the scales of the vertical axes between W-2, North Danville, and the Treynor catchments should be noted. Much less error is associated with the prediction of the small discharges measured for the W-2, North Danville catchment.

All figures confirm the tendency (although there are one or two exceptions) towards overprediction (negative error) during the early stages of the storm, then a swing upwards to underprediction (positive error) during the period of peak discharge and a tendency back to overprediction during the latter stages of recession. A similar pattern in errors was exhibited for the North Creek (figure 50) and Sixmile Creek (figure 51) catchments.

A plot of error versus the measured discharge for a variety of experimental frames is provided in figure 80 for W-2, North Danville and in figure 81 for the four Treynor catchments. Figure 80 illustrates clearly the overprediction for storm 3 (figure 80(A)) and underprediction for storm 6 (figure 80(B)). In addition, for storm 6 there appears to be an almost linear relationship between error and measured discharge. Indeed these two series have a correlation coefficient of 0.99. This is statistically significant at the 95% significance level.

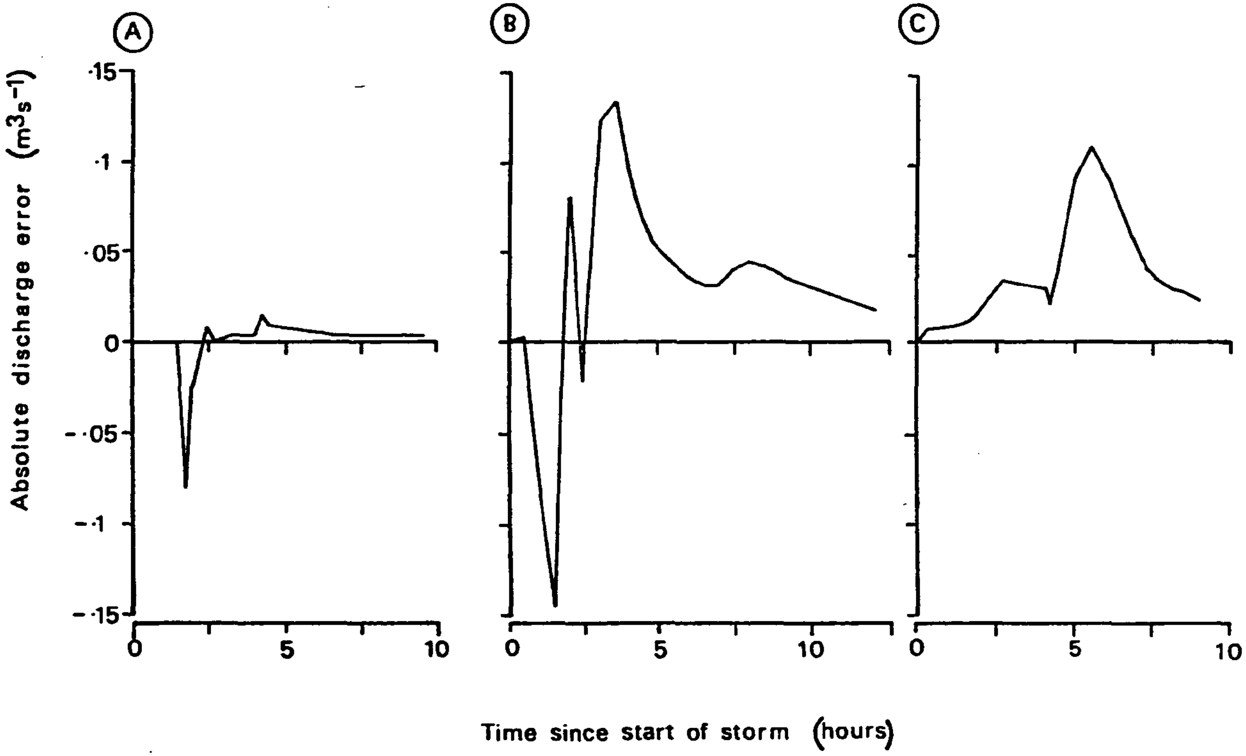


Figure 78 Absolute discharge error for W-2, North Danville (A) Storm 3, 28 August 1970 (B) Storm 4, 16 June 1967 (C) Storm 6, 2 June 1961

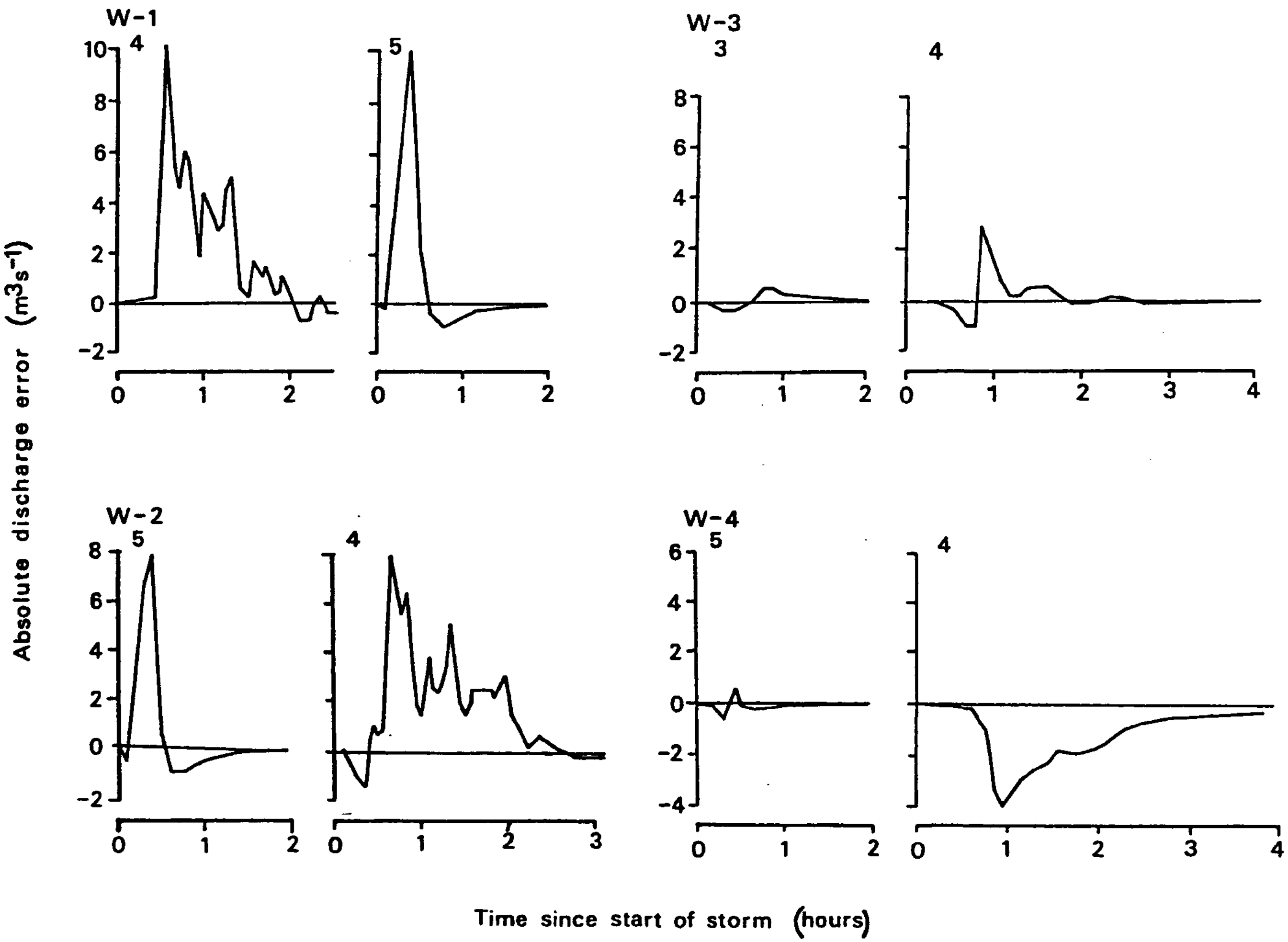
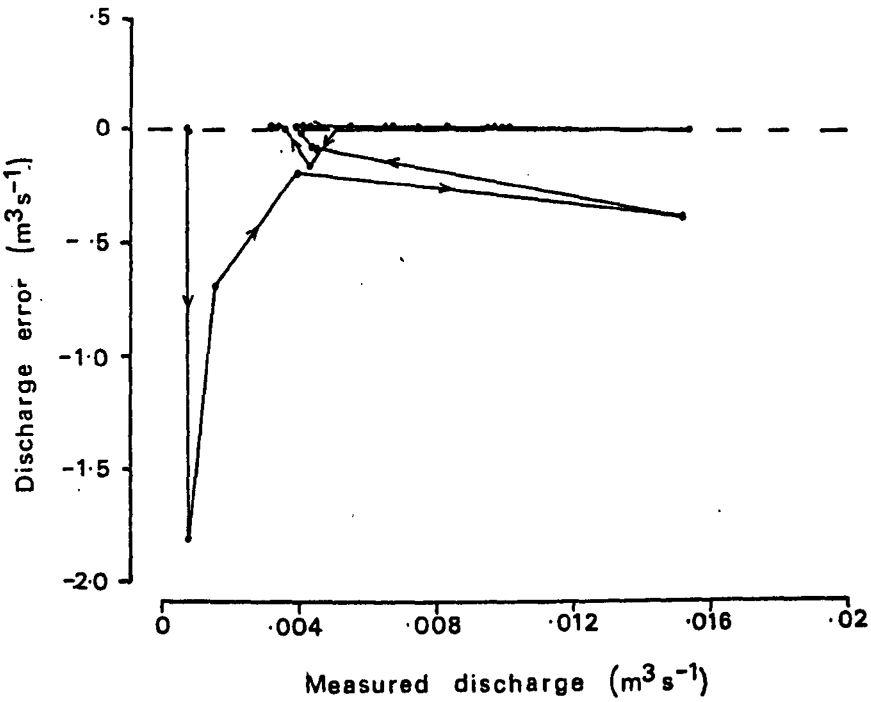


Figure 79 Absolute discharge error for a range of storms applied to the four watersheds near Treynor, Iowa (Each specific experimental frame is labelled on the figure)



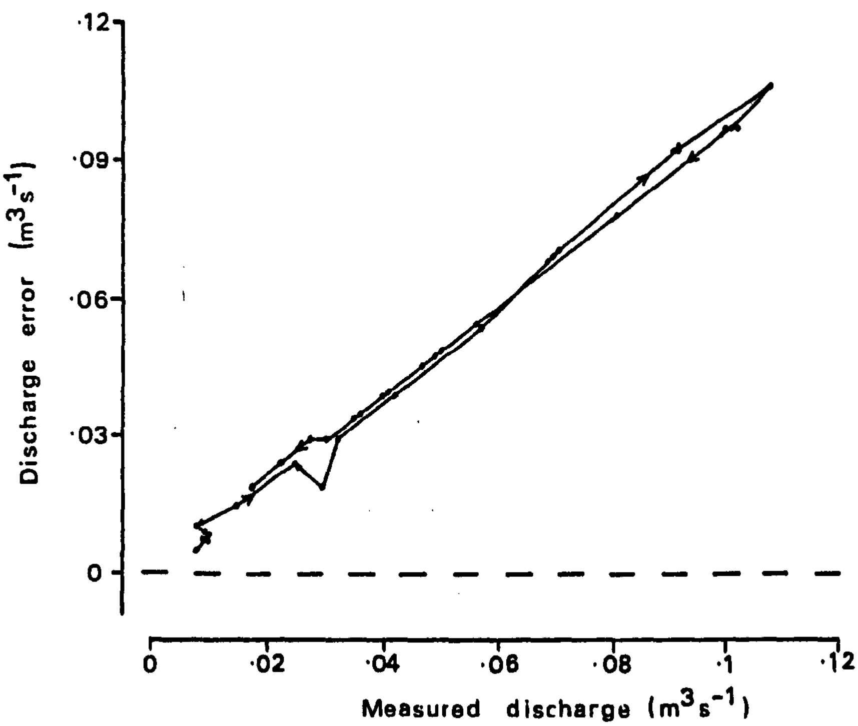


Figure 80 Relationship between discharge error provided by HYMO2 and measured discharge for W-2, North Danville (A) Storm 3, 28 August 1970 (B) Storm 6, 2 June 1961

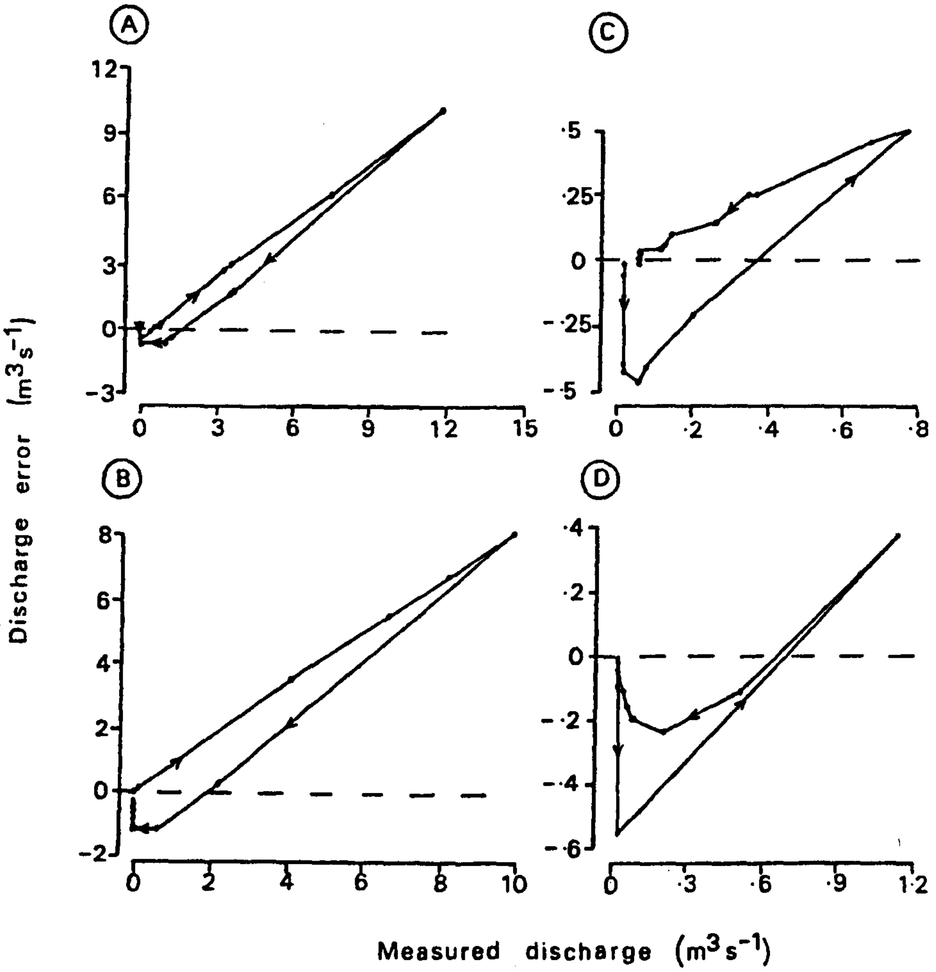


Figure 81 Relationship between discharge error provided by HYMO2 and measured discharge (A) Storm 5, 7 June 1967, W-1, Treynor (B) Storm 5, 7 June 1967, W-2, Treynor (C) Storm 3, 14 June 1967, W-3, Treynor (D) Storm 5, 20 June 1967, W-4, Treynor

In figure 81, all four plots show similar systematic forms of error to the North Creek and Sixmile Creek. Storm 5 applied to W-1 (figure 81(A)) and W-2 (figure 81(B)).

The autocorrelation functions for a selection of representative storms for each catchment are indicated in figure 82. All of these functions indicate a much lower degree of autocorrelation of error than was the case for the North Creek and Sixmile Creek. Many autocorrelation coefficients approach zero by lag 8. However, the systematic source of error in model prediction is still significant.

The mean and standard deviation of errors is provided in figure 83. Noticeably, a mean very close to zero and a small standard deviation are exhibited by North Danville, due mostly to the nature of the small discharges which are involved. The standard deviation of error is greatest for W-1 and W-2, where one standard deviation ranges from 2.66 to 0.8 $m^3 s^{-1}$. For W-3 and W-4, on the whole, the standard deviations are much lower (0.9 to 1.1 $m^3 s^{-1}$). Over all 26 experimental frames, 17 mean errors are positive and range from 0.1 to 1.44 $m^3 s^{-1}$ indicating underprediction by the model (meausured greater than calculated). The negative errors range from -0.1 to -1.08 $m^3 s^{-1}$.

The correlation coefficients in table 35 indicate that for none of the storms documented here are the errors normally distributed.

To conclude this section which compared the predicted and measured hydrographs for a variety of storms and for 5 catchments in Vermont and Iowa, the following two points can be made:

1 HYMO2 does not appear to provide very satisfactory predictions for W-2, an unnamed tributary of the Sleepers River catchment, near North Danville, Vermont, when this catchment is treated as an ungauged catchment. It is possible that improved predictions for each storm could be derived if a degree of fine tuning of the model parameters of HYMO2 were to be undertaken. This however, is not the point of this particular exercise. It is important to establish the degree of

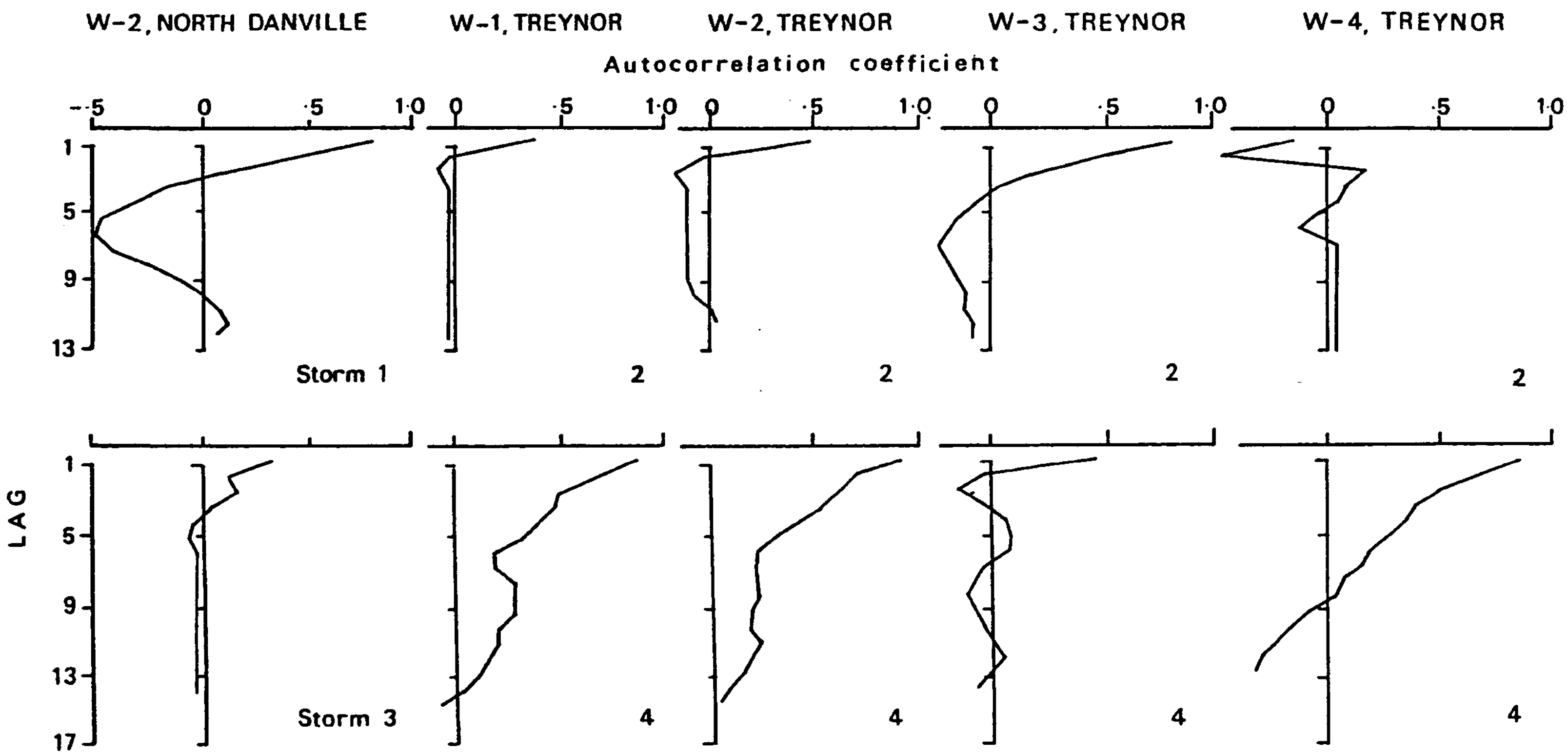


Figure 82 Autocorrelation coefficients for discharge error provided by HYMO2 for a range of catchments and storms

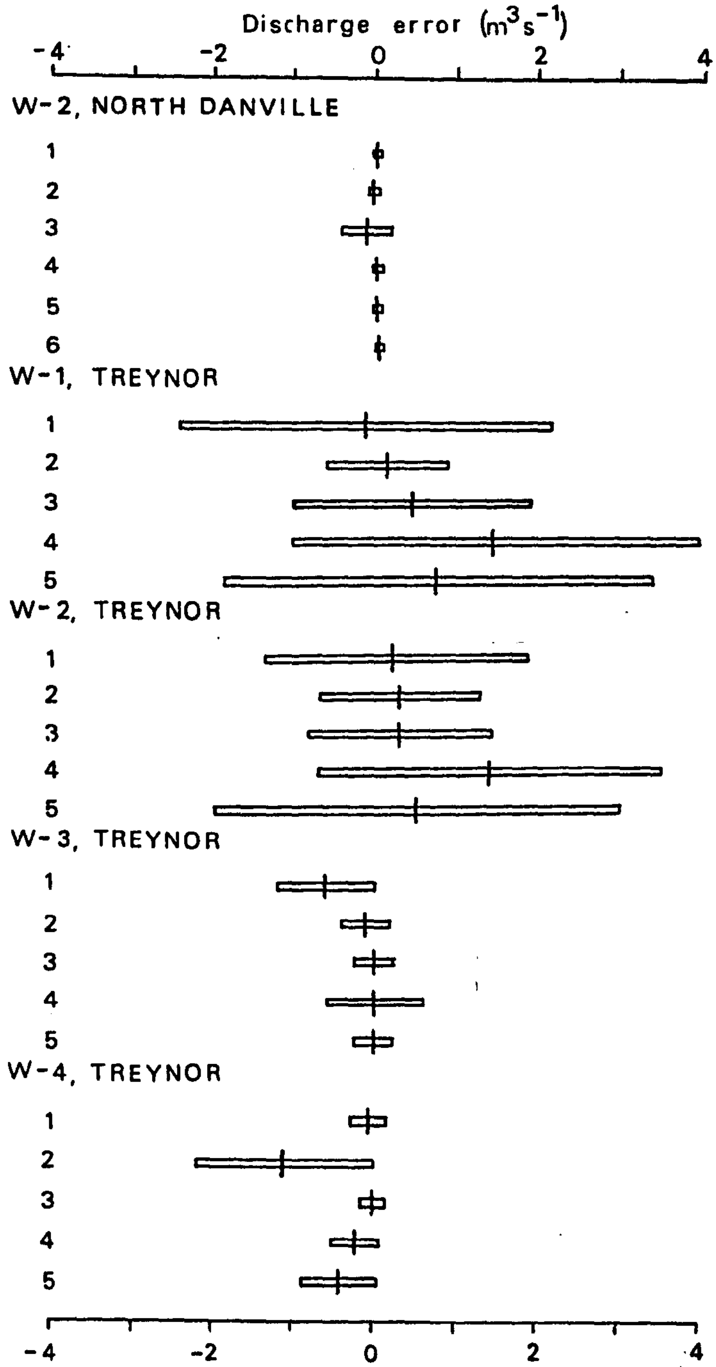


Figure 83 The mean (vertical line) and one standard deviation (horizontal bar) of discharge error, for 26 experimental frames

Table 35: Correlation coefficients for normal probability plot of error for all experimental frames, for all catchments in Vermont and Iowa

Catchment	Correlation coefficients					
	Storm numbers					
	1	2	3	4	5	6
W-2, North Danville Vermont	0.917	0.693	0.567	0.915	0.942	0.938
W-1, Treynor, Iowa	0.750	0.618	0.658	0.899	0.734	
W-2, Treynor, Iowa	0.670	0.763	0.640	0.915	0.767	
W-3, Treynor, Iowa	0.901	0.840	0.980	0.781	0.906	
W-4, Treynor, Iowa	0.889	0.852	0.908	0.928	0.889	

No coefficient in this table is statistically significant at the 95% significance level accuracy which can be obtained from model predictions for the ungauged catchment. Error in the hydrograph predictions was for the North Creek and Sixmile Creek, attributed to model and data error. The likely sources of model error in the context of the application to W-2, North Danville will now be examined.

There is a large probability that HYMO2 is inappropriate for application to this particular catchment. Dunne and Black (1970a, 1970b) document observations and measurements of the runoff producing mechanisms which occur in a small area of the Sleepers River catchment and they suggest that there is limited evidence to suggest that these general conclusions may be extrapolated for most of the watershed. The major runoff producing mechanism is overland flow from small and variable contributing areas located adjacent to the stream, in poorly drained positions where the water table is near to the surface. Runoff from these areas reaches the channel very quickly. HYMO2 is not designed to model these particular hydrological processes in terms of the methods used to generate runoff and the use of unit hydrograph procedures to route this runoff through the catchment area. Hortonian overland flow occuring over large areas has not been observed on this catchment and indeed, the infiltration capacity of the soils exceeds most measured rainfall intensities.

There is not such a high probability that data errors will be large for this catchment. As an ARS experimental watershed, it is likely that precipitation and measured hydrograph information will be as reliable as possible. It is possible however, that the soils data which are derived from the Brakensiek and Rawls charts are not accurate for simulation in this small catchment.

2 For the four catchments located near to Treynor, Iowa, again when they are treated as ungauged catchments, a wide range of predictions is derived. Overall, very similar patterns (but not magnitude) of discharge prediction error are obtained as were derived from application to the North Creek and Sixmile Creek. The timing of the

predicted hydrographs is good, but peak discharge is commonly underpredicted and a systematic source of error is identified, where mean errors differ from zero, are not normally distributed, and exhibit autocorrelation.

It is possible that this might provide additional evidence of an inappropriate model structure which was discussed in chapter 5. Again, improvements to the unit hydrograph, the most likely source of such systematic error, can be suggested. Certainly, the dimensionless unit hydrograph method which is used by HYMO2 has not been calibrated for catchments containing contour corn, located in Iowa, whereas it has been for Texas and Arkansas. This feature may also be connected with the scale of the catchments, it is possible that better predictions will be derived for larger catchments than the small ones.

6.4 Infiltration behaviour

Few cases of physically unrealistic infiltration behaviour were experienced in any application of HYMO2 which has been considered in this thesis. Unrealistic behaviour can be demonstrated to occur in association with a combination of very small cell size in the soil column, small time increments, and high precipitation intensity.

Figure 84 illustrates the precipitation and resulting infiltration and runoff behaviour for all five soil types in the W-2, North Daville, Vermont for storm number 4. Infiltration is represented by the changing moisture content of the five soil columns at three depths, 0.05 metres, 0.15 metres and 0.3 metres every 30 minutes from 04:30 hours (the start of the storm), for 9 hours (storm duration). For each soil type, the most rapid and greatest increase in soil moisture content is experienced at the shallowest depth indicated. The increase in soil moisture content further down the soil column is not as great, and occurs more gradually. Runoff occurs in association with saturated surface

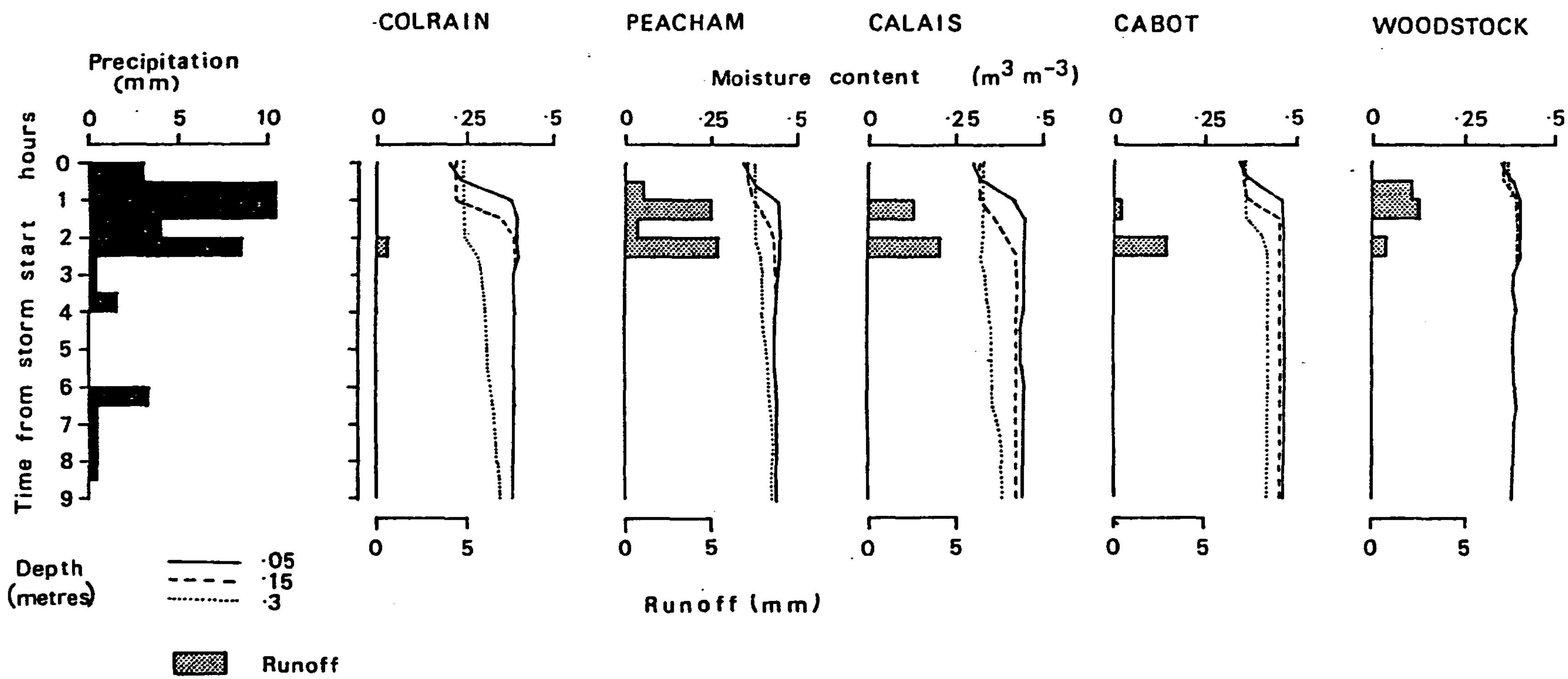


Figure 84 The runoff behaviour and change in soil moisture conditions at 3 depths which is predicted by the infiltration model for all 5 soil types in W-2, North Danville, for storm 4, 16 July 1967

conditions and higher rainfall intensities. Where a greater amount of precipitation is required to saturate the soil (Colrain compared to Peacham, for example), less runoff results.

Figure 85 illustrates the effect which the choice of the cell size and iteration period has upon infiltration behaviour, again as represented by changes in soil moisture content. These results were derived from application of a storm of 22 June, 1964 (which has not previously been used in this thesis) which has a total of 27.94 mm precipitation to the soil column Ida (a silt loam) which occurs in the watersheds near Treynor, Iowa. This soil, in the absence of more detailed data, is assumed not to be layered and is represented by a soil column comprising 6 cells. The location of the midpoints of each cell is indicated in figure 85, and the hydrological characteristics have been derived from the centroid position on the Brakensiek and Rawls charts. Figures 85(A), 85(B), and 85(C) all illustrate the initial moisture content and the moisture content at successive 6 minute intervals for each cell. Figure 85(A) illustrates the response when a 30 second iteration period is assumed; figure 85(B) if a 10 second period is assumed; and figure 85(C) where both a 10 second iteration period and twice as many cells, with halved cell dimension are used. There is very little difference between the soil moisture content profiles which develop during the storm when the 6 cells are utilized, and iterations of 30 or 10 seconds are used. Halving the cell size, however, has no effect during the first 4 time intervals, but during the next 3 time intervals, a form of physical instability occurs and moisture content oscillates through a range of 0.2 $m^3 m^{-3}$. This instability corresponds to periods where large amounts of precipitation occur. When the precipitation amount drops again, for intervals 8 to 10, the profile resumes a physically realistic form and one which is similar to those attained in figures 85(A) and 85(B). It is interesting to note that associated with these conditions is a value of (BAL) (equation 48), a measure of the mean numerical error, of 0.015 for condition 'C' compared with a value of 0.010 for condition 'A'. No benefit is seen to be derived from the adoption of smaller cell sizes and shorter time increments.

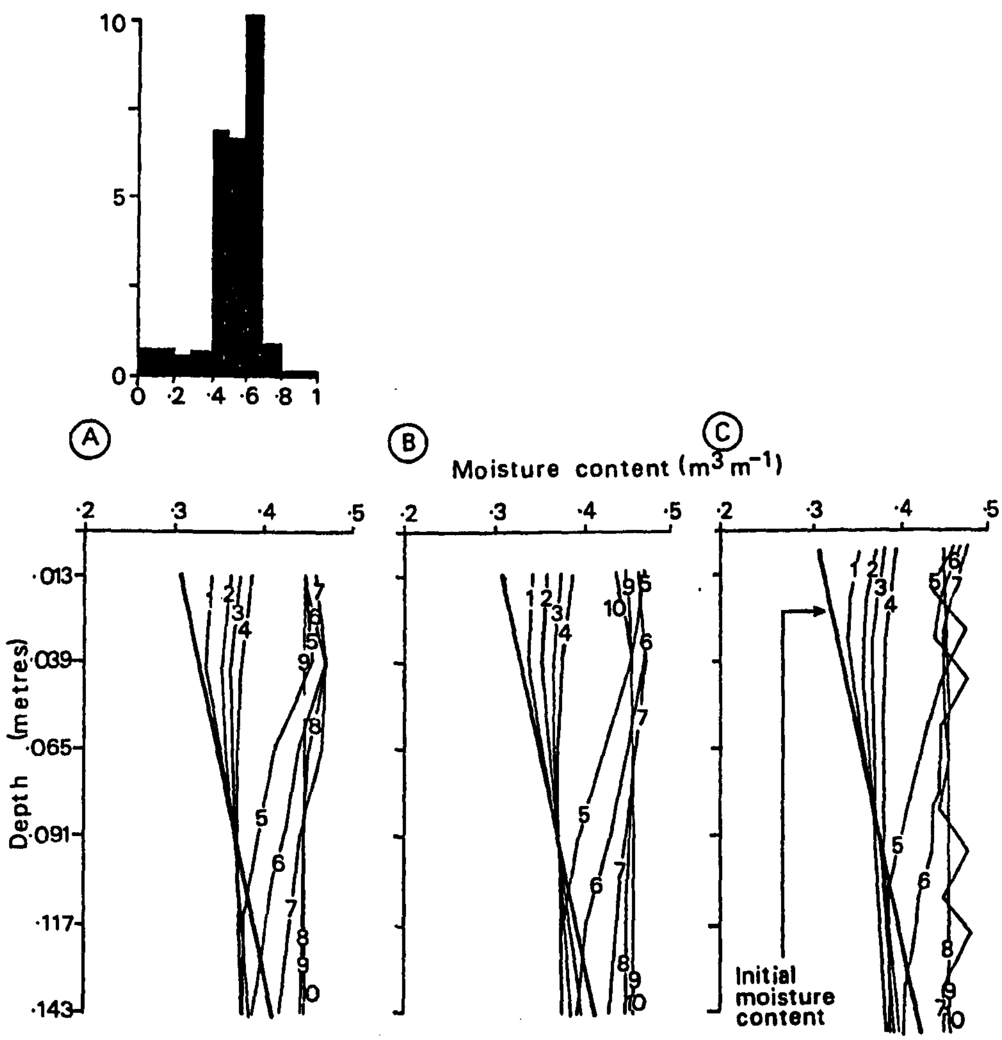


Figure 85 A comparison of the change in moisture context at 6 minute intervals which are predicted by the infiltration model for the Ida silt loam, and associated with the application of a storm of 22 June 1964 (total precipitation 27.94 mm) for (A) a 30 second iteration period (B) a 10 second iteration period (C) a 10 second iteration period and halved cell dimensions

6.5 Finite difference method

Section 4.3 demonstrated very low values for (BAL), a measure of the magnitude of numerical errors incurred by the solution of the Richards equation using an explicit finite difference method, for a range of hypothetical storm situations. Slightly higher errors are exhibited for more complex soil and precipitation conditions. Table 36 provides the details of the value of (BAL) for each soil type on all seven catchments located in Texas, Arkansas, Vermont and Iowa for all storms which have now been documented. For many cases, the value of (BAL) can be related to soil depth, soil type, and precipitation intensity. For example, the results presented in table 36 for North Creek, Texas illustrate that greater errors occur for the soil column representative of the Gowen-Pulexas soil groups. This soil column is deeper than those representing the Bonti-Cona-Truce and Thurber-Hasse soil groups, and consequently has a greater number of cells for which a solution must be provided. The Gowen-Pulexas also has a higher conductivity than the other two soils, which both have clay in layers 2 and 3 (tables 24, 25, and 26). The lowest error for the Gowen-Pulexas soil occurs for storm 3. This storm has the shortest duration (1.3 hours) and the most precipitation (107 mm). In contrast, the greatest error for this soil type occurs for storm 1 which is 8.25 hours long and throughout is very erratic; periods of high precipitation intensity alternate with periods of very little rain. Such rapid fluctations in rainfall intensity in successive time intervals appear to be associated with greater errors in the solution of the Richards equation.

Very similar relationships between soil characteristics and the value of (BAL) are exhibited by the information provided for the storms applied to the Sixmile Creek. Larger errors are associated with the deeper soil, Leadvale. However, for this suite of storms, there is no clear relationship between (BAL) and storm characteristics.

For W-2, North Danville, the magnitude of error is very much less than has been noted for the previous two catchments. This may be related to

Table 36: Numerical error (BAL) derived for all experimental frames and all catchments

Storm number	BAL^* ($\times 10^{-2}$ m^3m^{-3})		
	Soil types		

North Creek, Texas

	Gowen-Pulexas	Bonti-Cona-Truce	Thurber-Hasse
1	-9.3	-4.4	-2.0
2	-8.8	-5.1	-1.8
3	-6.0	-2.6	-0.9
4	-8.2	-3.8	-0.2
5	-8.8	-4.1	-1.2
6	-9.0	-2.5	-1.3

Sixmile Creek, Arkansas

	Leadvale	Enders	Mountainburg
1	-0.6	-0.2	-0.2
2	-0.7	-0.2	-0.2
3	-3.6	-0.4	-1.0
4	-4.3	-0.2	-0.1
5	-1.1	-0.6	-0.5
6	-0.6	-0.1	-0.8

W-2, North Danville, Vermont

	Colrain	Peacham	Calais	Cabot	Woodstock
1	0.0	-0.1	0.0	-1.1	-0.5
2	0.0	0.0	0.0	0.0	-0.4
3	0.0	0.0	0.0	-0.3	-0.5
4	-0.2	0.0	0.0	-1.3	-1.2
5	0.0	-0.3	-0.1	-1.6	0.0
6	0.0	0.0	0.0	0.0	-0.2

W-1, Treynor, Iowa

	Mona	Marshall	Napier	Ida
1	-0.4	0.0	0.0	-3.9
2	-0.1	0.0	0.0	-1.1
3	0.0	0.0	0.0	-0.7
4	-3.2	0.0	0.0	-12.6
5	-0.4	0.0	0.0	-2.2

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Table 36 ... continued from previous page

Storm number	BAL* ($\times 10^{-2}$ m^3m^{-3})			
	Soil types			
	Mona	Marshall	Napier	Ida
W-2, Treynor, Iowa				
1	-0.3	0.0	0.0	-2.3
2	-0.1	0.0	0.0	-0.9
3	0.0	0.0	0.0	-0.8
4	-3.3	0.0	0.0	-11.9
5	-0.3	0.0	0.0	-3.0
W-3, Treynor, Iowa				
1	-0.3	0.0	0.0	-2.8
2	0.0	0.0	0.0	-1.4
3	0.0	0.0	0.0	-0.9
4	-2.0	0.0	0.0	-9.2
5	-0.1	0.0	0.0	-0.8
W-4, Treynor, Iowa				
1	-2.7	0.0	0.0	-2.8
2	0.0	0.0	0.0	-0.9
3	0.0	0.0	0.0	-0.9
4	-2.0	0.0	0.0	-9.2
5	-0.1	0.0	0.0	-0.8

* BAL is defined in equation (48) in the text

the shallow soil columns which were used to represent the soils of this catchment. The greater amount of numerical error is not consistently associated with the same soil column. The Cabot soil type exhibits the greatest error for storms 1, 4, and 5, and the Woodstock soil type for the remaining three storms. These two soils do not have any particular characteristics in common, and the deepest soil for this catchment with the greatest number of cells is Colrain.

For all 4 catchments near Treynor, the soil column representing the Ida soil type exhibits the greatest error. This soil column is the shallowest, but the cell dimensions are the smallest. For all four catchments, the greatest error is experienced for storm 4. This storm has the highest precipitation total, but also, as noted for Texas, the most rapidly alternating successions of high and low intensity rainfall. The lowest error for W-1 and W-2 is associated with storm 3 which has the lowest total precipitation. The lowest error for W-3 and W-4 is associated with storm 5 which has the second lowest pecipitation total, but the shortest duration.

The relationship of error to precipitation is demonstrated in figure 86. The information for this figure is taken from storm 4 applied to W-1, Treynor. Cumulative precipitation is compared to cumulative (BAL) for the two soil columns which, as indicated in table 36, exhibit errors in solution. A steeper gradient on the cumulative precipitation curve appears to be related to a steeper rise in the value of cumulative BAL for each soil type. Indeed, the correlation coefficient between cumulative precipitation and the cumulative (BAL) for Monona soil type is 0.964 and for the Ida soil, is 0.997. Both of these correlation coefficients are signficant at the 95% confidence level.

Over all experimental frames, it is not considered that numerical errors are large enough to justify an examination of alternative numerical techniques.

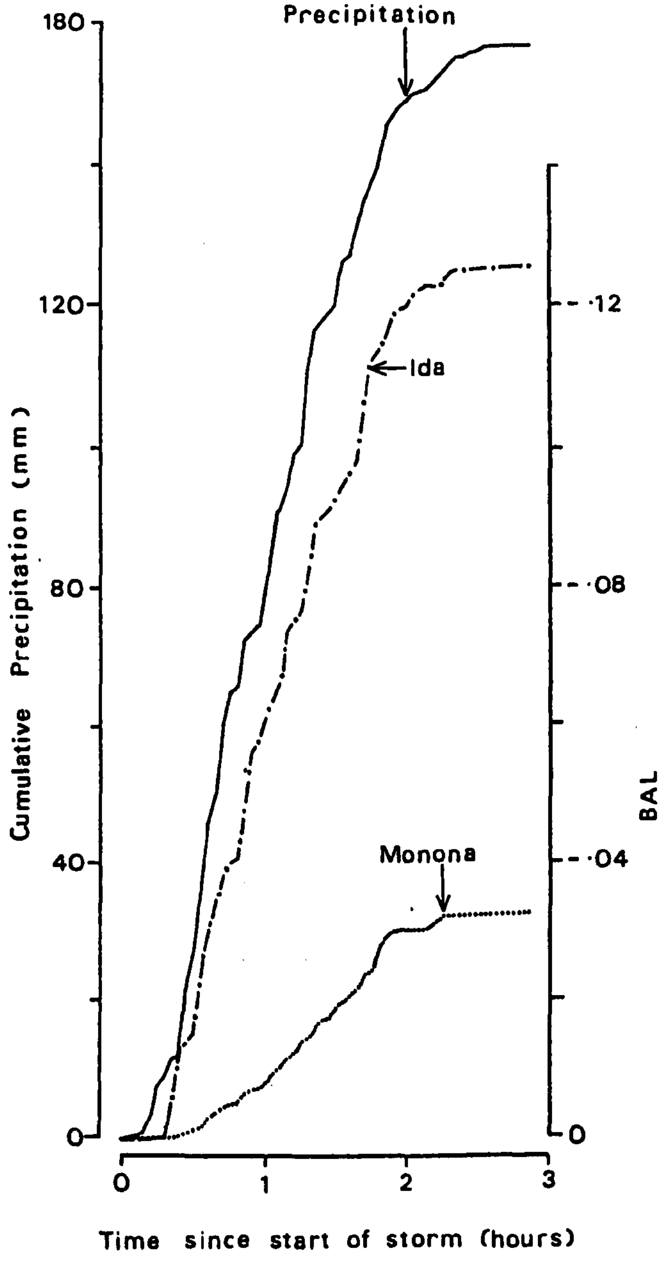


Figure 86 Relationship of numerical error (BAL) to precipitation for the Monona and Ida soil types for storm 4, 16 July 1967, applied to W-1, Treynor

6.6 Summary of applications

To summarize the results of the application of HYMO2 to 38 storms, and for a range of seven catchments in Texas, Arkansas, Vermont, Iowa, figures 87, 88, and 89 have been produced. Figure 87 attempts to assess the accuracy of HYMO2 for the prediction of peak discharge; figure 88, the accuracy of the time to peak discharge predictions and figure 89, the closeness of the overall hydrograph form. From these figures, the following comments may be derived:

1 Prediction of peak discharge

Figure 87(A) provides a plot of calculated versus measured peak discharges for all 38 experimental frames. A correlation coefficient of 0.911 between these two series has been calculated. This is statistically significant, but the trend towards underprediction of peak discharge, which has been noted previously, is seen clearly. This type of plot, although often produced in modelling studies, is slightly misleading in that the very small deviations from the dashed line (indicating perfect prediction) in the lower peak discharge range can be, in relative terms, a good deal more significant than the apparently larger deviations which occur at higher discharges. This point is illustrated by figure 87(B), where percentage peak discharge error (given by equation 30) is plotted against measured discharge. Much greater error is seen to be associated with the prediction of lower peak discharge than with higher. Indeed, this figure suggests that the closest estimate of peak discharge, provided by HYMO2, will be derived for peak discharges between the range 20 to 65 $m^3 s^{-1}$. There is a greater tendency towards overestimation within the lower discharges, and underestimation at higher.

Figure 87(C) provides a plot of percentage peak discharge error versus total precipitation. From this range of experimental frames, there does not appear to be a clear relationship between these two series. However, it could be suggested that in general, greater accuracy is provided by

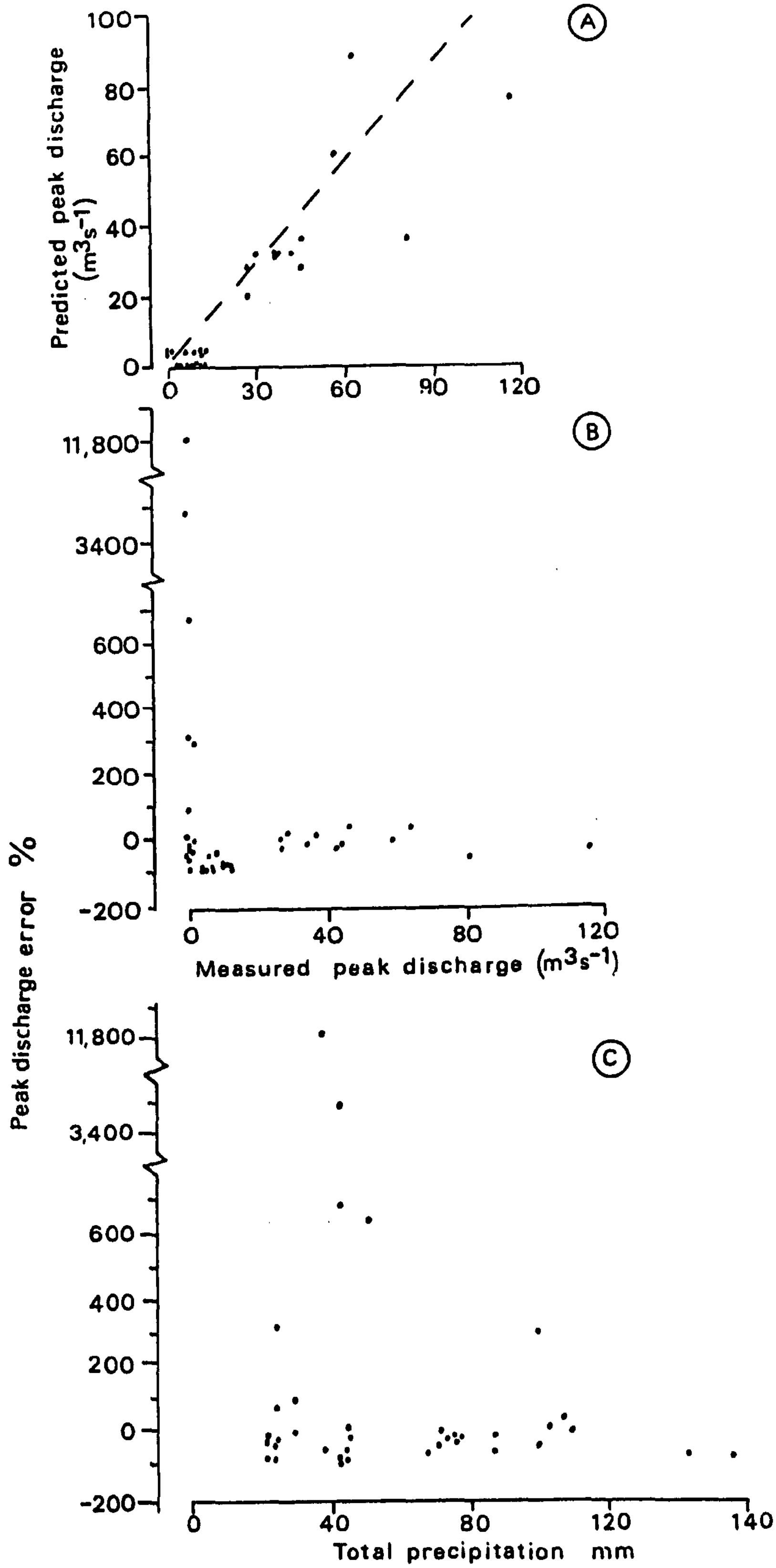


Figure 87 A summary of the accuracy of HYMO2 for the prediction of peak discharge over all 38 experimental frames (A) the relationship of calculated and measured peak discharge (B) the relationship of percentage peak error and measured peak discharge (C) the relationship of percentage peak discharge error and total precipitation

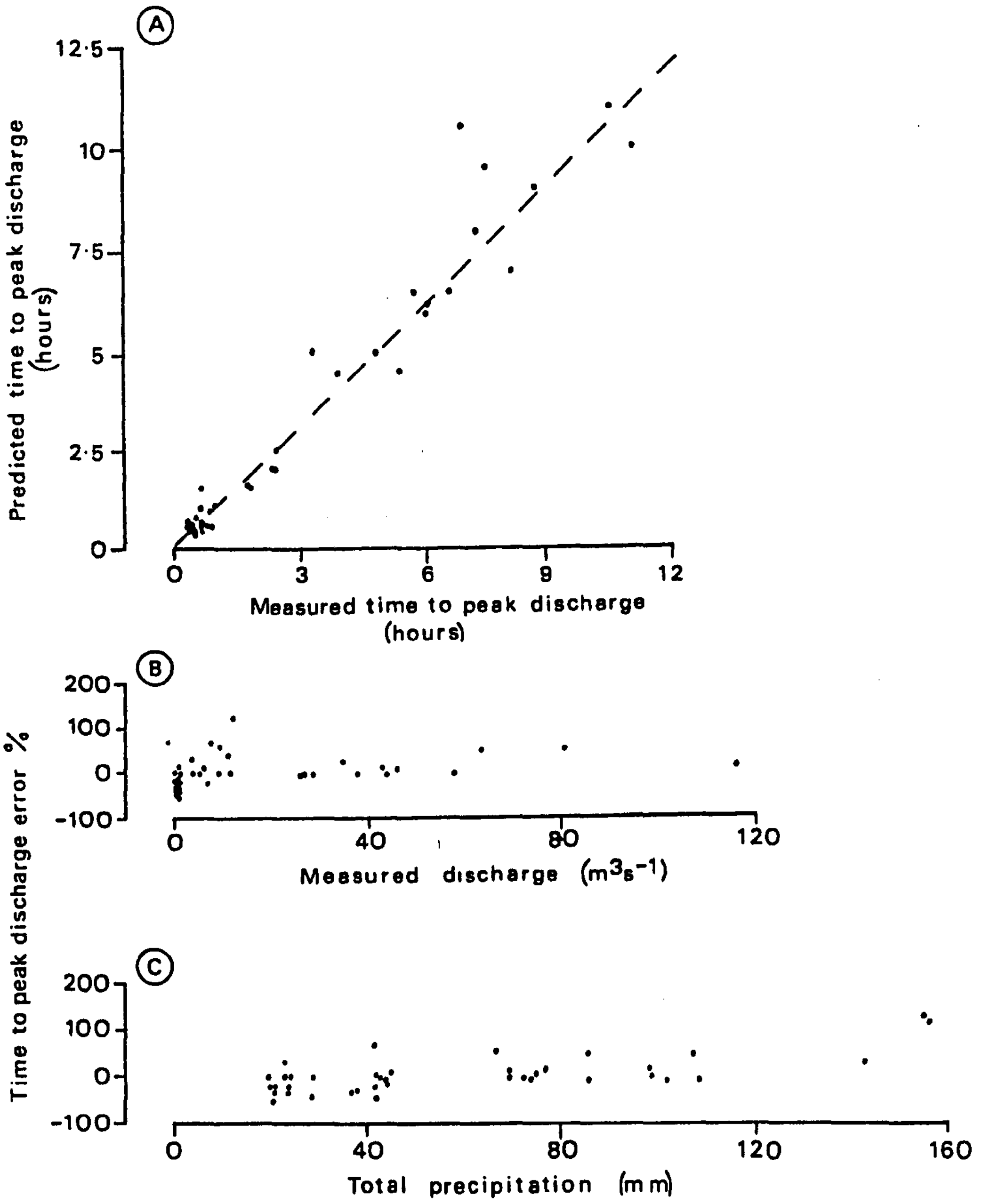


Figure 88 A summary of the accuracy of HYMO2 for the prediction of the time to peak discharge over all 38 experimental frames (A) the relationship of calculated and measured time to peak discharge (B) the relationship of percentage time to peak discharge error and measured peak discharge (C) the relationship of percentage time to peak discharge error and total precipitation

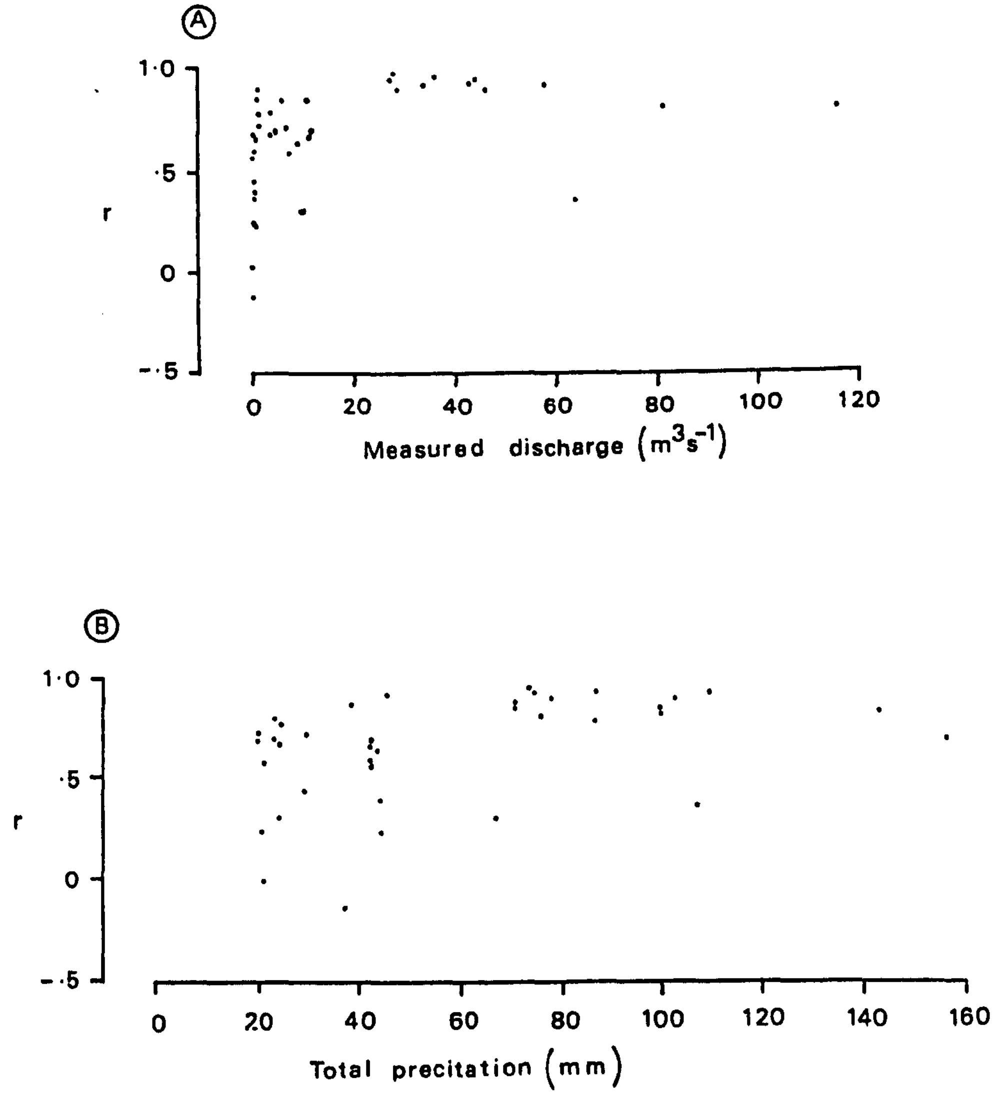


Figure 89 A summary of the accuracy of HYMO2 for the prediction of the overall form of the discharge hydrograph for 38 experimental frames (A) the relationship of the correlation coefficient (r) the measured peak discharge (B) the relationship of the correlation coefficient and total precipitation

the modified model for the prediction of the peak discharge for larger storms.

2 Predictions of time to peak discharge

HYMO2 predicts the time to peak discharge much more accurately than any other hydrograph characteristic. The correlation between calculated and measured time to peak discharge, indicated in figure 88(A), is 0.974. This is higher than that calculated for the association between calculated and measured peak discharge. Figure 88(B) indicates that over the total range of measured peak discharges which are considered in this study, a much lower percentage error for time to peak discharge is derived, than for peak discharge. There are just one or two outliers, for example at 12 $m^3 s^{-1}$. This can be identified as the error associated with the prediction of time to peak discharge for storm 4, W-1, Treynor. As the other errors for this hydrograph characteristic are much lower, this outlier might possibly be associated with error in the precipitation or measured hydrograph data which were utilized for this particular storm event. Figure 88(C) also indicates very little clear relationship of percentage time to peak discharge error to precipitation totals.

3 Predictions of the overall form of the discharge hydrograph

The closeness of form of the calculated to measured hydrograph is, for the purposes of this comparison, indicated by the value of the correlation coefficient. Figure 89(A) provides the distribution of the correlation coefficient according to measured peak discharge. On the whole, a closer association is derived for hydrograph events where peak discharge ranges between 20 and 60 $m^3 s^{-1}$. Below and above these values, the correlation coefficient between the calculated to measured increases in range. Figure 89(B) indicates no clear relationship between the correlation coefficient and total storm precipitation, although very generally, the closeness of fit does have a tendency to improve as the total precipitation increases.

HYMO2 does also appear to provide more accurate predictions for some catchments than others. To assess the overall goodness of fit of the calculated hydrographs for the range of storms applied to each catchment, a multiple index (I_x) was derived from the percentage peak discharge error (PDE), percentage time to peak error (TPE), and the correlation coefficient (r) according to the following expression:

$$I_x = | \, PDE \, | + | \, TPE \, | + 100(1-r) \qquad (68)$$

This index was evaluated for each experimental frame, and the mean value was derived for each catchment. The results of this are presented in table 37. For the range of storms which have been considered in this analysis, the best predictions are derived for the Sixmile Creek, Arkansas, and then for the North Creek, Texas. The model does not appear to provide suitable predictions for the unnamed tributary, W-2, of the Sleepers River catchment. In comparison to this catchment, it was more successful for the four catchments near Treynor, Iowa. In this context, it should be recalled that the unit hydrograph procedure has been calibrated for 34 catchments located in Texas, Oklahoma, Arkansas, Louisiana, Mississippi, and Tennessee.

Application of HYMO2 has so far provided a range of results and has pointed to a possible source of systematic error in the model predictions, the unit hydrograph. Chapter 7 will provide a series of comparisons of the original HYMO and HYMO2 to establish that HYMO2 does provide improvements in hydrograph predictions in a number of areas.

Table 37: Multiple index (I_x*) of overall hydrograph fit for all experimental frames, and for all catchments

Catchment	Value of I_x for each storm						Mean value of I_x
	1	2	3	4	5	6	
North Creek, Texas	62	45	150	104	9	42	69
Sixmile Creek, Arkansas	62	18	7	24	27	23	27
W-2, North Danville, Vermont	69	402	11961	71	139	211	2142
W-1, Treynor, Iowa	196	149	139	229	117		166
W-2, Treynor, Iowa	188	104	117	125	116		130
W-3, Treynor, Iowa	758	185	159	69	47		244
W-4, Treynor, Iowa	3557	28	80	322	55		808

* I_x is defined in equation (68), in the text

7

Comparison of HYMO and HYMO2

HYMO has been described in chapter 2 (section 2.1). Included in the hydrological procedure for the hydrograph computation is the SCS curve number model (USDA SCS, 1972) for incremental runoff derivation. HYMO has a suitable structure to meet operational and ungauged requirements. However, as section 2.2 has emphasized, it has not been noted for accuracy in the hydrograph predictions which it provides.

In section 2.2, the curve number model was identified as one possible cause of this inaccuracy. The curve number model is used to derive estimates of incremental runoff associated with a particular storm event for the ungauged catchment. It is an empirical model which is described by equation (17) and which has been designed for application at a catchment scale. It provides a convenient lumped expression of net catchment hydrological characteristics. Runoff, the proportion of precipitation which appears as direct runoff on the catchment, is related to precipitation by an estimate of catchment storage, and by an initial abstraction of 20%. Catchment storage is estimated as a function of the catchment curve number. The curve number is a dimensionless coefficient which reflects the soil hydrological group, land use, agricultural treatment or practice, and antecedent soil moisture conditions of the catchment area.

As indicated in section 2.2, the SCS curve number model does have certain attractions. It is simple to understand, quick and efficient to use, requires little data, is well established and accepted, and has good, or at least a good quantity of, documentation. However, the model has attracted certain quite fundamental criticisms. The problems associated with the model can very broadly be divided into two categories: conceptual problems, and problems relating to more technical issues.

Conceptual problems

Certain criticisms have been made of the theoretical basis of the curve number model, the inadequate treatment which is given to antecedent soil moisture conditions, and the very coarse and therefore inappropriate division of soils into four hydrological divisions. Criticisms have also been made of the unrealistic infiltration behaviour which is predicted by the model in response to erratic precipitation characteristics.

Technical problems

There are three technical problems with the curve number model:

1 Problems are incurred during parameter estimation. The selection of curve numbers for the ungauged catchment is a time consuming process, and in addition, it is very difficult to derive objective estimates of the catchment curve number. Ungauged estimates of curve numbers tend to be much lower than the associated calibrated values. The calibrated values can be derived from equation (19), for circumstances in which precipitation and runoff totals are known.

2 The curve number model does have a tendency to underpredict the measured runoff values associated with a storm event. The incorporation of this model into HYMO therefore causes underpredictions to be made of peak discharge. In addition however, the general form and the timing of the predicted hydrographs provided by the original HYMO which incorporates the curve number model are not considered to approximate the measured values very closely.

3 The runoff predictions provided by the curve number model are highly sensitive to the curve number value which is estimated for the catchment area. To illustrate this point, section 2.2 has drawn attention to the evidence provided by Smith (1976) which has

demonstrated that HYMO's predictions are more sensitive to the curve number than to precipitation data.

The fundamental nature of these problems indicates that the curve number model has therefore been retained by HYMO not on the basis that it is the most logical choice of model for predicting incremental runoff, but merely to retain model simplicity, computational efficiency, minimum data requirements, model acceptability, ease of use, and mainly because a suitable alternative model, which fulfils the ungauged and operational requirement, has not been available.

The infiltration model which has been described in this thesis does represent a viable and, it is to be argued in this chapter, a superior alternative to the curve number model as a procedure for the prediction of incremental runoff within HYMO2. The infiltration model has been developed specifically to simulate the infiltration behaviour which occurs during a storm event. It is therefore particularly suitable for predicting incremental runoff. In addition, the infiltration model has been specifically designed and structured to fulfil ungauged and operational requirements.

In this chapter therefore, it is interesting to provide a series of direct comparisons between HYMO2, the modified version incorporating the infiltration model, and HYMO, the original version which utilized the curve number model. It is important to establish that improvements to HYMO have been effected by the replacement of the empirical curve number model with a physically based infiltration model. This chapter is designed to illustrate that, in particular, improvements have been achieved in the following four areas:

1 Improvements in the conceptual basis of the model

The conceptual basis of the curve number model has been criticizied on a number of points. It will be illustrated that in comparison, the infiltration model does have a sound conceptual basis.

2 Improvements in parameter estimation
A number of problems are associated with the selection of curve numbers for the ungauged catchment. It will be illustrated that a greater degree of direction can be provided for the user undertaking data collection and preparation for the operation of the infiltration model.

3 Improvements in prediction accuracy
A series of comparisons of measured hydrographs to those provided by both HYMO2 and original HYMO will serve to illustrate the improvements in prediction accuracy which are derived by the replacement of the curve number model by the infiltration model.

4 Improvements in parameter sensitivity
A demonstration of the sensitivity of the predictions provided by HYMO to the curve number value will be provided to illustrate the favourability of the much lower degree of sensitivity which is experienced by HYMO2 to a selection of infiltration model parameters.

Each of these improvements will now be considered.

7.1 Improvements in the conceptual basis of the model

Certain criticisms have been made in the literature concerning the basis and development of the curve number method in the context of its application within HYMO. These have been detailed in subsection 2.2.2 and include questions concerning the fundamental assumptions of the relationship between precipitation, runoff, and catchment storage upon which the model is based and which have been raised by Morel-Seytoux and Verdin (1981). Many authors consider that the curve number model does not make adequate provision for antecedent soil moisture conditions in the catchment, for initial abtractions which vary with storm event, and for variable precipitation characteristics. It has been stressed in subsection 2.2.2 that the curve number model has been applied out of context. The model was not designed for the prediction of incremental runoff associated with a particular storm event, but was originally designed and intended to provide estimates of total catchment runoff for a 24 hour period, and thus only requires daily rainfall totals. Consequently, the model does not include time as an independent variable and it is not therefore surprising that the infiltration behaviour which is predicted by the model during a storm event has been demonstrated by Morel-Seytoux and Verdin (1981) and Hjelmfelt (1980a) to be unrealistic, and contrary to theory. The incorporation of the curve number model into HYMO is therefore not logically sound. The model is not designed to indicate the distribution of runoff within a 24 hour period and cannot therefore be used to provide estimates for incremental runoff associated with a particular event.

In contrast, the infiltration model has, within the context of the ungauged and operational application which has been discussed in sections 1.1 and 1.2, been demonstrated in chapter 3 to be conceptually and hydrologically sound.

The infiltration model has been specifically designed for application to the ungauged catchment. It is a physically based model which is founded upon the Richards equation, and which does not require calibration. The mathematical formulation and solution of the Richards equation which have been applied in this model are simpilified enough to meet the constraints of the ungauged and operational requirement. The ungauged catchment provides only a limited data supply both in terms of quantity and quality, and the operational requirement insists that limits to both computer resources and the experience of the user in application of the particular model must be assumed. Simplification of the mathematical formulation of infiltration involves the assumption of one dimensional soil water movement and simplifying assumptions concerning infiltration behaviour and soil characteristics. The infiltration model and its solution, however, remain realistic enough to predict infiltration behaviour which, as has been demonstrated in sections 4.1 and 6.4, is realistic both for a range of hypothetical and more complex conditions.

The errors introduced by the numerical method of solution have been analysized in sections 4.3 and 6.5, and were shown to be relatively small.

In the past, the empirical curve number model was considered to be the only suitable model which could be used for predicting incremental runoff and which also met the constraints imposed by an ungauged and operational application. This model no longer represents the most logical choice to satisfy these criteria. In particular, certain advances in the application of more physically based models, numerical solution techniques, and an increased availability of the soils data which are necessary for the application of these models now means that physically based models can be considered as suitable alternatives for operational requirements. Physically based models are conceptually superior to empirical models for the ungauged application as they do not, when formulated in a suitable manner, require calibration.

In the context of this application therefore, it is considered that significant conceptual improvements have been made to HYMO by the replacement of the empirical curve number model by the physically based infiltration model.

7.2 Improvements in parameter estimation

The derivation of ungauged estimates for curve numbers involves a look-up procedure involving a number of tables (tables 8, 9, and 10) which have been produced by the SCS. Information concerning soil hydrological group, land use, hydrological condition, agricultural treatment, and antecedent soil moisture conditions, is required to derive the ungauged curve number for a catchment. This look-up procedure, including the derivation of composite curve numbers for larger, heterogeneous catchments, has been well documented by the SCS, and in addition, tables have been produced for more specific vegetation and soil complex covers, such as rangeland. Despite this wealth of documentation, ungauged curve number values do tend to underestimate the calibrated values associated with any storm event. Bales and Betson (1982) provide evidence of this underestimation for a range of 585 events, and indeed this can also be demonstrated for a selection of experimental frames which have been utilized in this thesis. Figure 90 illustrates the calibrated (represented by a circle) and ungauged (vertical bar) estimate for a range of storms applied to the North Creek, Texas, Sixmile Creek, Arkansas, and W-1 and W-2, Treynor, Iowa. For 17 of the 22 conditions indicated by figure 90, the estimated ungauged curve number is less than the calibrated value. In the case of storm 1, W-2, where the ungauged estimate is smaller than the calibrated value by 31, it is interesting to examine the significance of this difference in terms of runoff predictions for a range of storm totals. For storms of 25 mm, 50 mm, and 75 mm, the ungauged curve number provides runoff of 0.91 mm, 0.79 mm, and 6.35 mm respectively, and the calibrated curve number provides runoff of 11.1 mm, 23.5 mm, and 44.9 mm respectively. These represent quite significant differences in runoff predictions, and hence a very important problem for the curve number model.

There is no unique curve number for a particular storm or catchment situation, and two reasons can be suggested to account for the range of curve number values which are derived for the ungauged catchment:

1 The SCS curve number tables were originally derived, or calibrated, for a range of small catchment areas which exhibited homogeneity in soil and land use cover. Very little information has been published on the characteristics of the storms which were used, despite a known correspondence of the curve number to storm characteristics. For example, Hawkins (1978a) demonstrated that as rainfall totals increase, calibrated curve number values decrease. A constant curve number, independent of storm size is therefore not always appropriate and extremes in storm intensities in particular can cause departures from these curve numbers. It is suggested that extrapolation of these calibrated curve number values to larger heterogeneous catchments, and also to storms displaying different characteristics

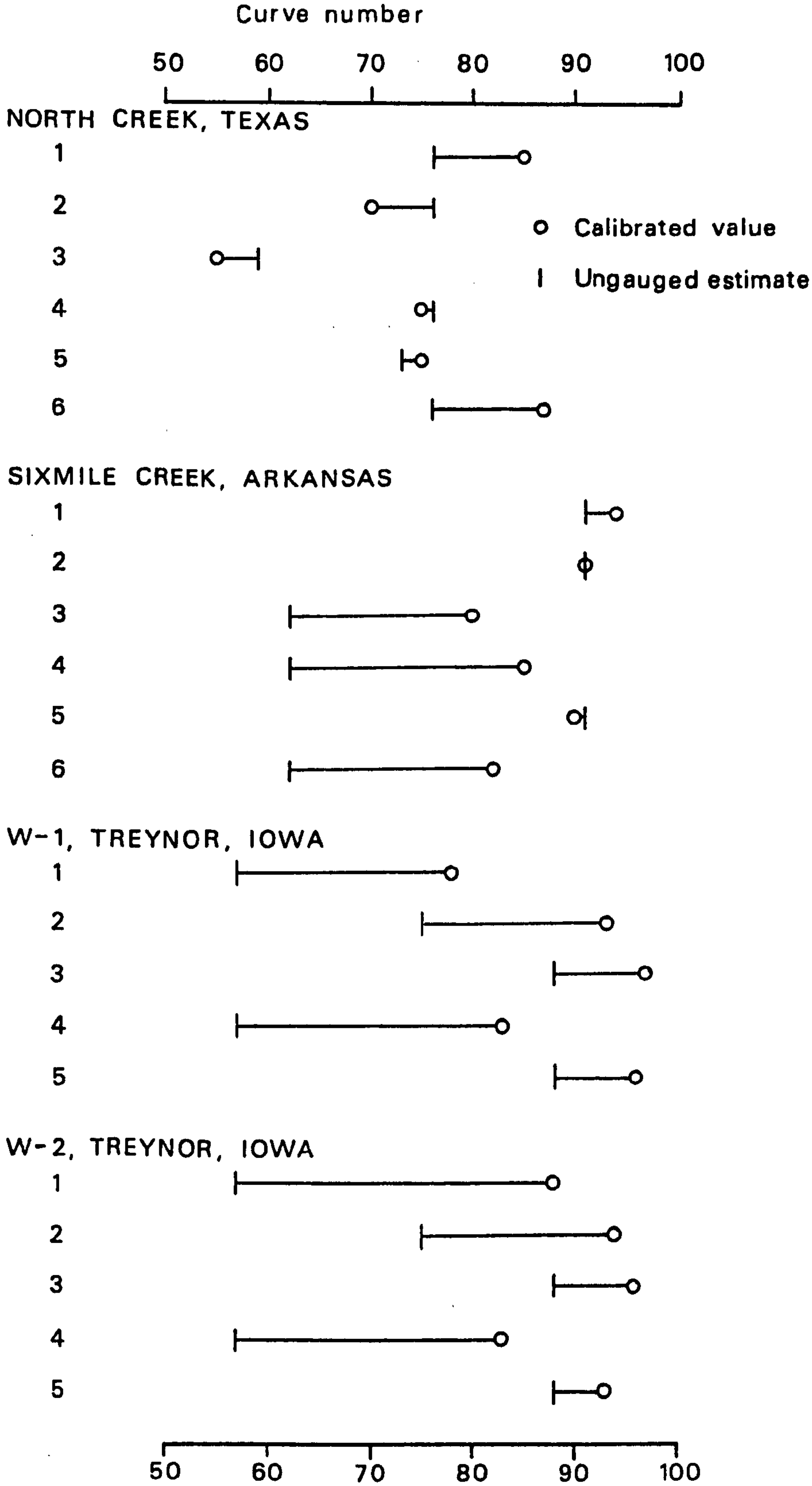


Figure 90 A comparison of ungauged and calibrated curve number values for a range of catchment and storm conditions

to those used in the calibration procedure could be one reason for this underestimation by the ungauged curve number values.

2 Despite very detailed documentation of the curve number method, parameter estimation remains largely a subjective procedure. Due to the subjective nature of the decisions which must be made during curve number estimation, it is not likely that any model operator would ever derive the same curve number value for any one catchment and antecedent soil moisture conditions should the estimation procedure be repeated. Indeed, Springer et al (1980) have stressed that in application of the curve number model to ungauged catchments, there must be some degree of local calibration if accuracy is required.

Alternative more accurate and practical methods of parameter estimation have been suggested for the curve number model. These methods include the use of remotely sensed data and geographic data bases (Rawls et al, 1981; Slack and Welch, 1980). Bondelid et al (1982) provided a comparison of the determination of curve numbers from conventional methods, which for a watershed area of 54 square km took two man months, and derived a curve number value of 63.5, to the determination using remotely sensed data and a digital geographic data base, which for the same catchment took 0.5 man days and provided a value of 64. These improvements in parameter estimation increase the level of information which is required and are therefore not considered to represent improvements to the model in the context of the ungauged and operational application.

The most significant advantage which the infiltration model has in comparison to the curve number model is that model parameters are physically based. The infiltration model parameters which include soil hydrological properties such as saturated hydraulic conductivity, saturated soil moisture content, soil moisture characteristic curve, and initial moisture content, are all properties which have physical interpretation and are therefore measurable.

Parameter estimation for the infiltration model can therefore include the use of measured values, or in the case of the ungauged catchment, published values from soils data bases such as SIRS (discussed in subsection 1.2.1), or by the application of empirical estimation techniques such as the Brakensiek and Rawls method. The Brakensiek and Rawls method has been presented in this thesis as a suitable method to derive certain soil hydrological parameters for the infiltration model. Although it is an empirical procedure, it has been demonstrated in section 5.1 to provide suitable data.

In comparison to the curve number method, with its Government agency origin, support, documentation, and longer history of application, there has been much less experience with application of the infiltration model. However, the applications of the infiltration model which have been presented in this thesis do indicate that with increasing experience in application, appropriate guidelines can be provided for the user to assist the data collection and preparation stages, and that not as much catchment detail is required in terms of land use information and agricultual treatment. In addition, the time involved in parameter estimation of the infiltration model is less than that involved in a systematic estimation of a single, integrated ungauged catchment curve number. It has been strongly suggested in section 6.2 that the empirical estimation of parameters for the infiltration model, and the experience gained in application of this model in terms of parameter estimation, be included in a section of the computer program which aids the preparation and formating the data required by the model. Interactive facilities between this information and the user will enable the user to draw upon the advantages of this experience without it necessarily being personal experience. The incorporation of this information into the program rather than in the form of model documentation is to be strongly recommended.

Thus certain improvements in parameter estimation are associated with the infiltration model, and consequently with HYMO2.

7.3 Improvements in prediction accuracy

A series of comparisons of the measured and calculated hydrographs derived from both HYMO and HYMO2 are presented in this section. To provide a complete comparison of all aspects of the predicted hydrographs, certain elements of the two stage procedure for model comparison which is indicated in figure 41 will be utilized. All experimental frames used in this section have been introduced in the previous two chapters, and each will be identified by catchment name and storm number. Tables 23 and 34 provide the details of each storm.

Stage 1: Comparison of hydrographs

A series of hydrograph comparisons, presented in the form of time series plots, are provided in figures 91 to 94, for a range of storms applied to catchments in Texas, Arkansas, and Iowa. The relationship of the predicted hydrographs provided by both models to the measured hydrograph, which is illustrated by this selection of experimental frames, is representative of a larger number of cases. Figure 91 provides a comparison of the predicted and measured hydrographs for storms 2 (figure 91(A)) and 6 (figure 91(B)) applied to the North Creek, Texas. For both storms, a closer approximation to the measured hydrograph is derived from HYMO2 in comparison to the original model. These improvements are reflected in both the timing and peak discharge characteristics of the predicted hydrograph. Figure 92 also illustrates that improvements in hydrograph predictions for the Sixmile Creek, Arkansas, are derived by application of HYMO2 to storms 3 (figure 92(A)) and 4 (figure 92(B)). Figures 93 and 94 indicate that HYMO incorporating the curve number model predicts a much smaller amount of runoff than was measured for the catchments in Iowa. Indeed, for W-3, storms 1 and 2, and W-4, storm 1 (not indicated in these figures), no runoff was provided by HYMO. Although HYMO2 does not represent the peaked nature of the measured hydrographs indicated in figures 93, and 94, and provides underestimates of the time to peak discharge in figure 94(A), it does appear to provide more accurate predictions than the original model.

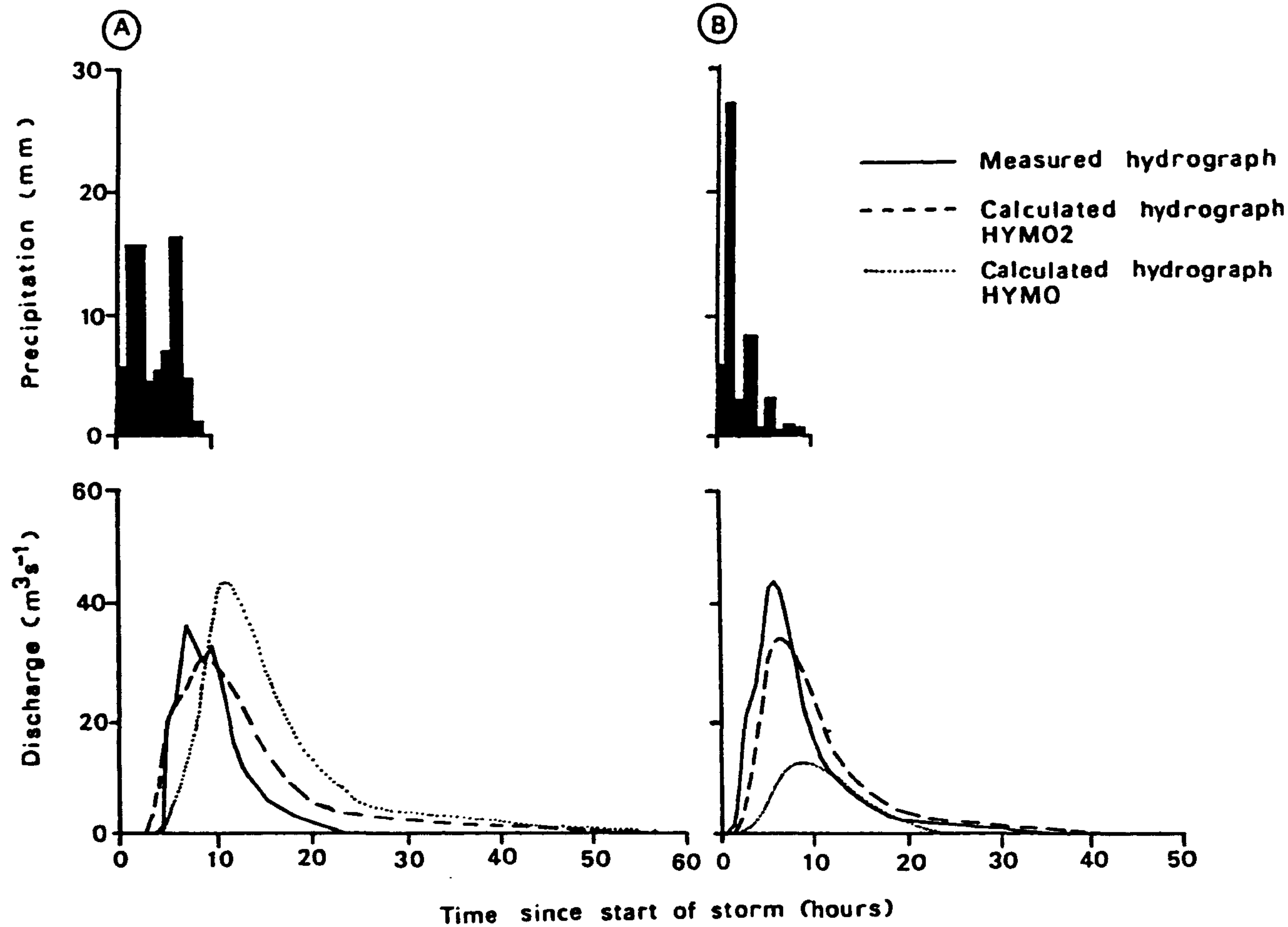


Figure 91 Comparison of measured hydrographs to those predicted by HYMO and HYMO2 for the North Creek (A) Storm 2, 27 July 1963 (B) Storm 6, 6 May 1969

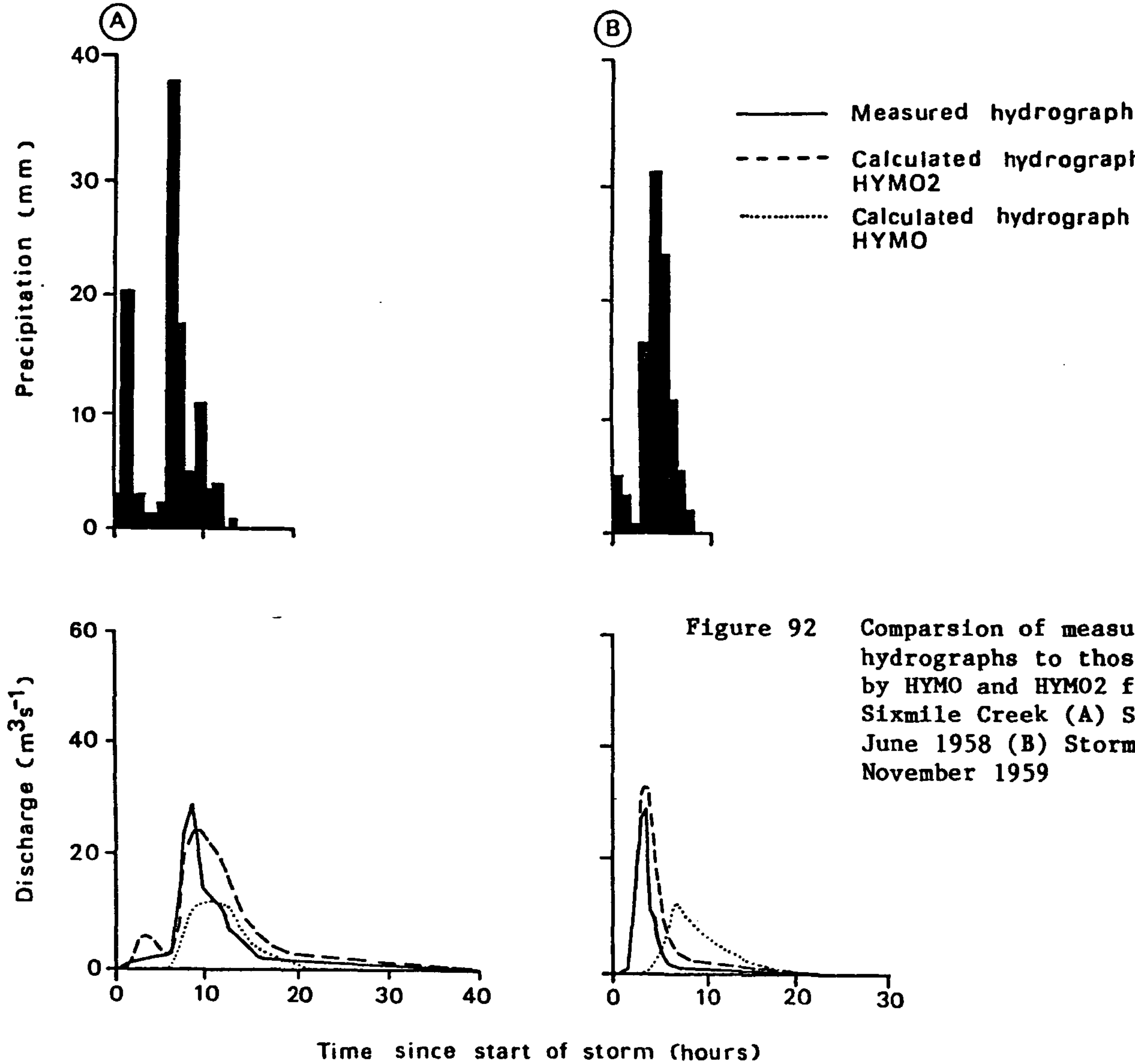


Figure 92 Comparsion of measured hydrographs to those predicted by HYMO and HYMO2 for the Sixmile Creek (A) Storm 3, 25 June 1958 (B) Storm 4, 3 November 1959

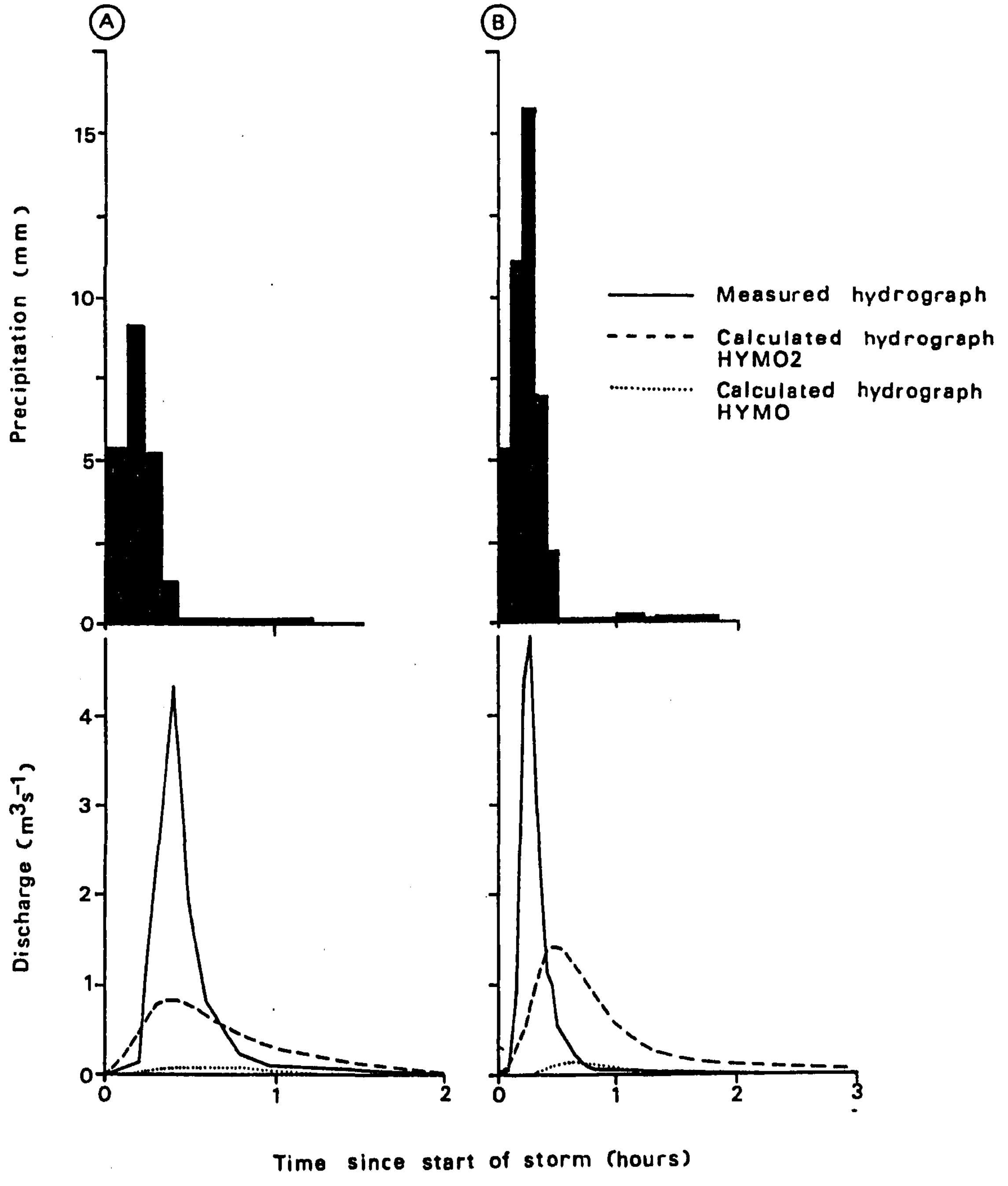


Figure 93 A comparison of measured hydrographs to those predicted by HYMO and HYMO2 (A) Storm 2, 26 June 1966, W-1, Treynor (B) Storm 1, 2 August 1970, W-2, Treynor

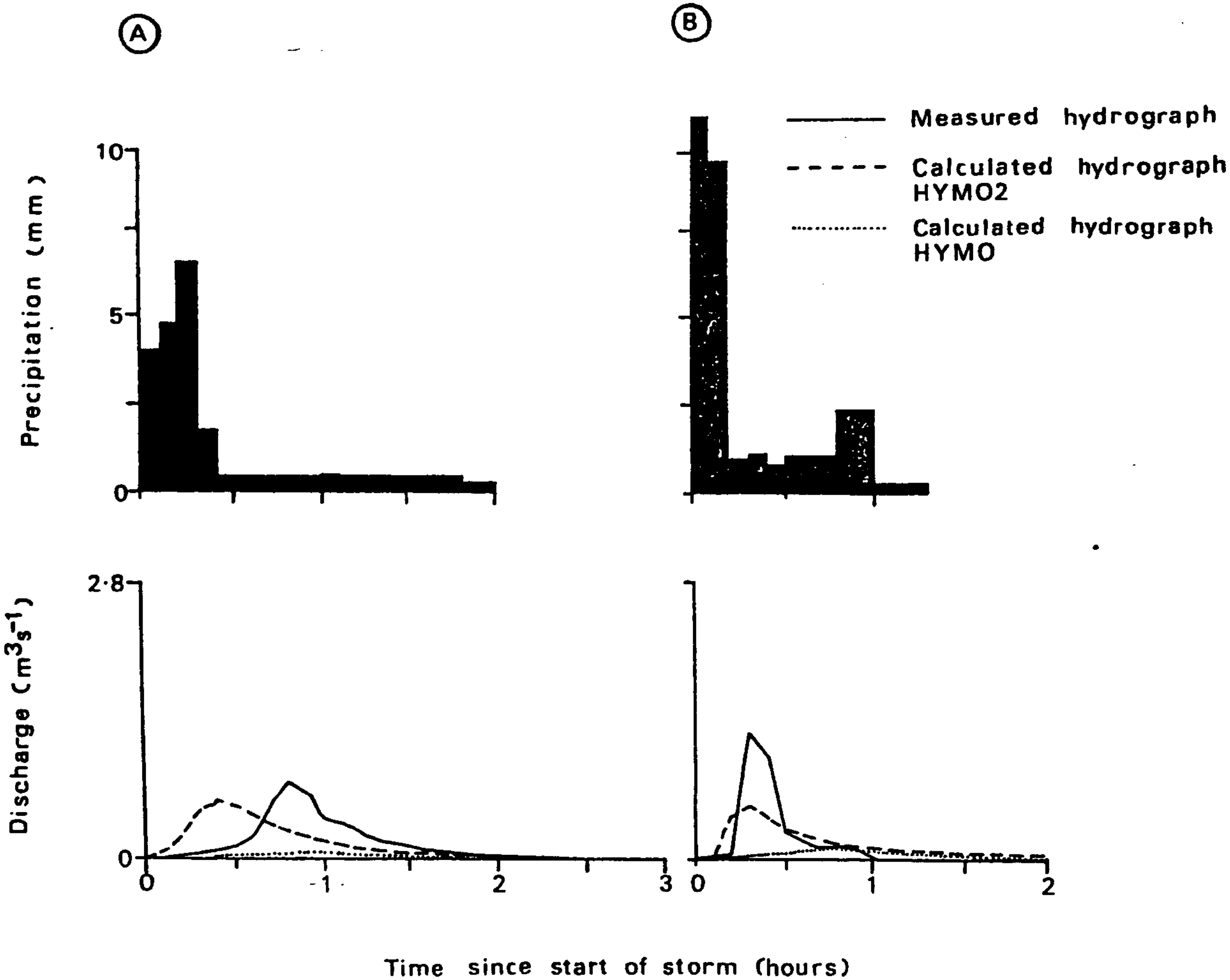


Figure 94 A comparison of measured hydrographs to those prdicted by HYMO and HYMO2 (A) Storm 3, 14 June 1967, W-3, Treynor (B) Storm 2, 25 June 1966, W-4, Treynor

Figure 95(A) indicates the relationship between calculated and measured discharge for storm 1, North Creek. This relationship has a very similar form to the relationship between the discharge calculated by HYMO2 and measured discharge which was illustrated in figure 47(A). The rising limb, peak discharge, and early phase of the recession limb are underpredicted, and the latter phase of the recession is overpredicted. The relationship produced by the original model however, is located further from the line of perfect prediction during the rising and peak discharge stages, indicating that improvements in prediction accuracy have been derived from HYMO2. However, the close similarity in the pattern and persistence of either overestimation or underestimation indicates that despite the improvements of HYMO2, there remains a systematic source of error. Figure 95(B) demonstrates that this now familiar relationship between the discharge calculated by model and the measured discharge also exists for storm 4, Sixmile Creek.

Figure 96 provides a comparison of the percentage time to peak discharge error for 32 experimental frames for HYMO and HYMO2. HYMO2 provides more accurate predictions for this hydrograph characteristic in all but 7 of the 32 cases illustrated. For 5 of these 7 cases, the same predictions are derived from both models, and therefore only for two cases are improvements in the time to peak discharge predictions gained by the retention of HYMO. In both of these cases, the percentage error difference is only in the order of 10%. As mentioned above, no runoff (indicated as ′nr′ in the figure) is predicted by the curve number model in the original model for three events. This figure therefore provides evidence that the selection of HYMO2 for all of these cases would be most appropriate.

Figure 97 provides a comparison of the percentage peak discharge error for the same 32 experimental frames used in figure 96, for HYMO and HYMO2. HYMO2 provides more accurate predictions of peak discharge in 22 of the 32 cases, HYMO provides the better predictions for five experimental frames, both models provide the same predictions for two, and the original model produces no runoff for three experimental frames. It is interesting to note that for two of the three cases where HYMO

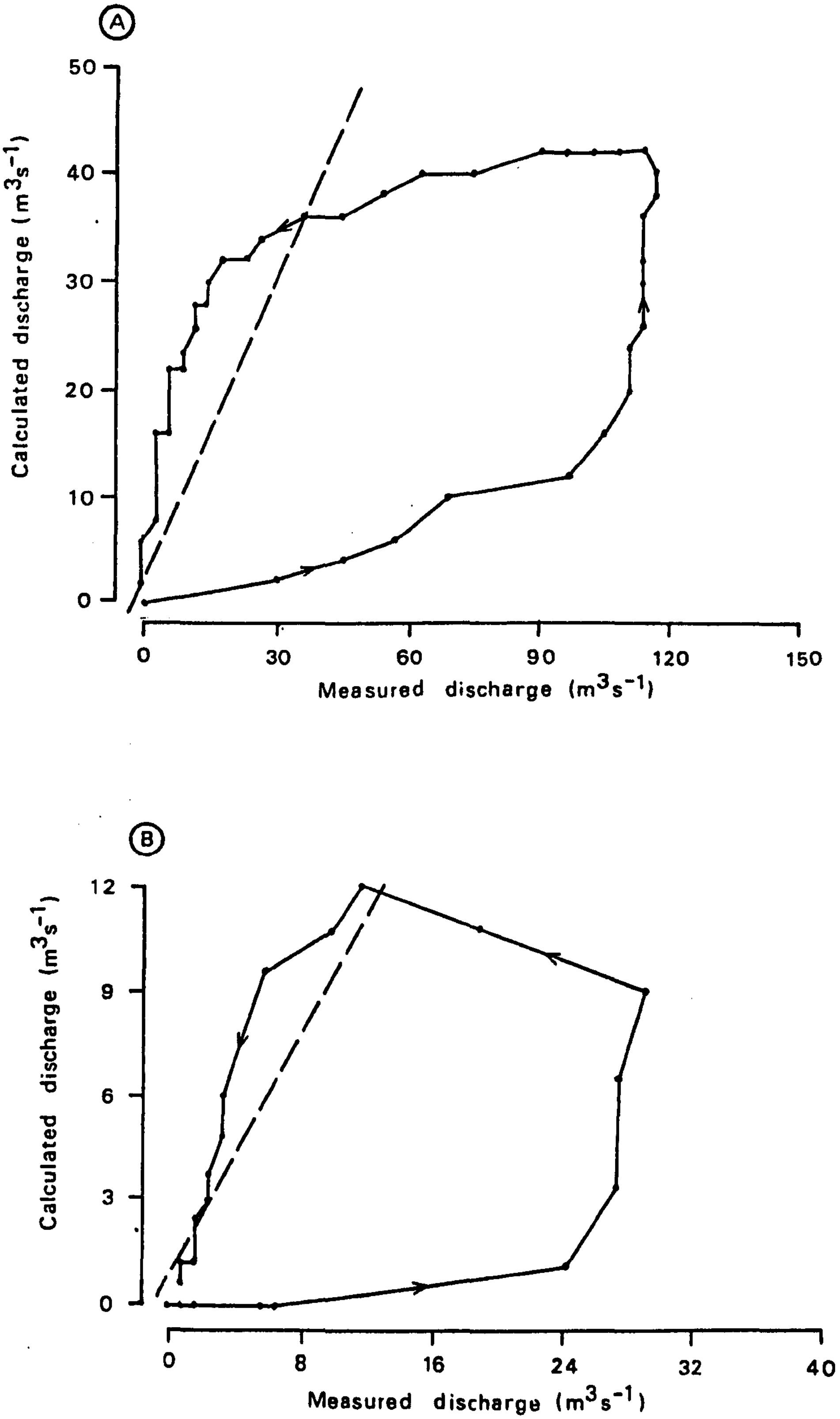


Figure 95 Relationship between discharge predicted by HYMO and measured discharge (A)) Storm 1, 9 October 1962, North Creek (B) Storm 4, 3 Novermber 1960, Sixmile Creek

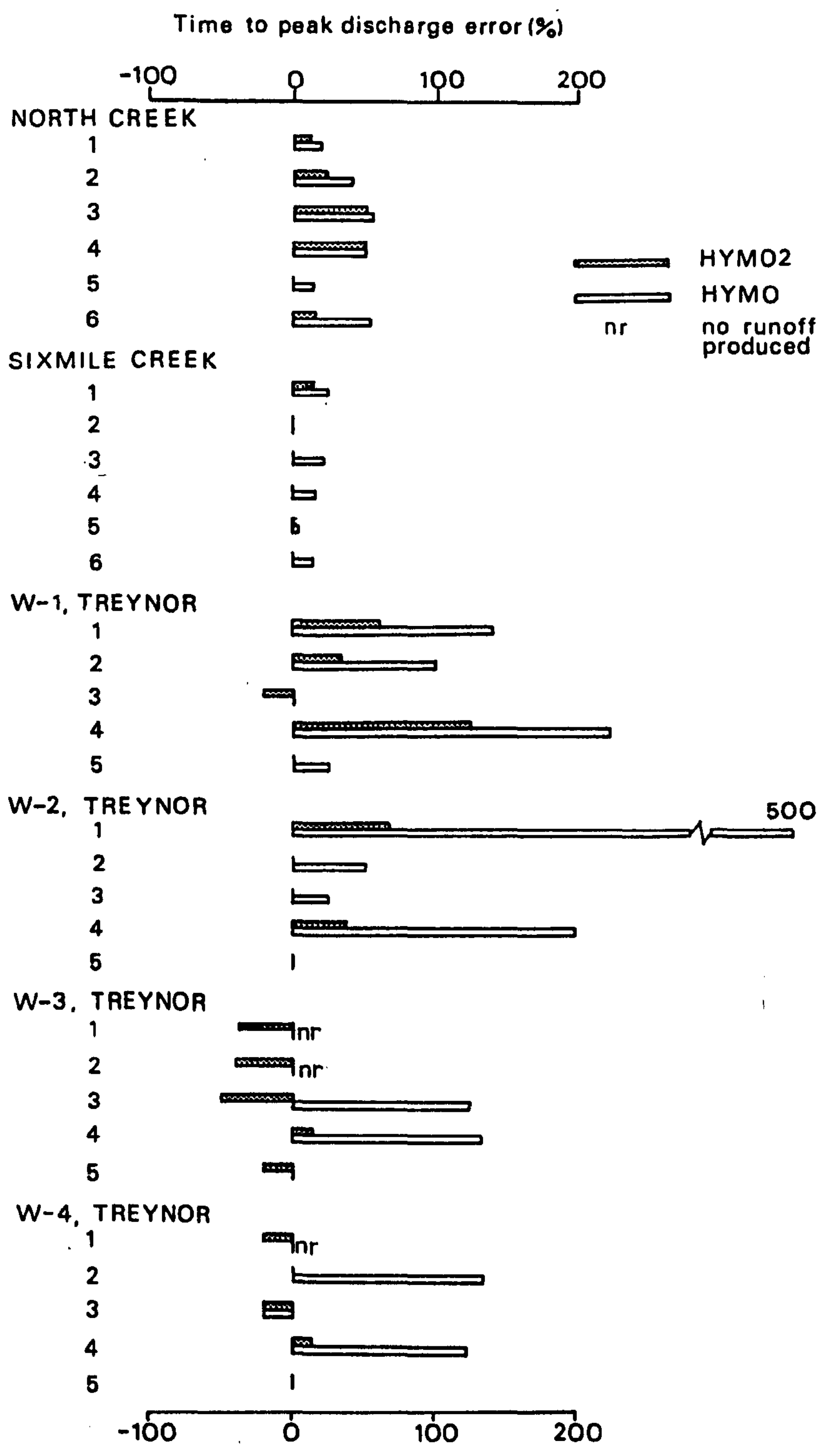


Figure 96 Comparison of the percentage time to peak discharge error of HYMO and HYMO2, for 32 experimental frames

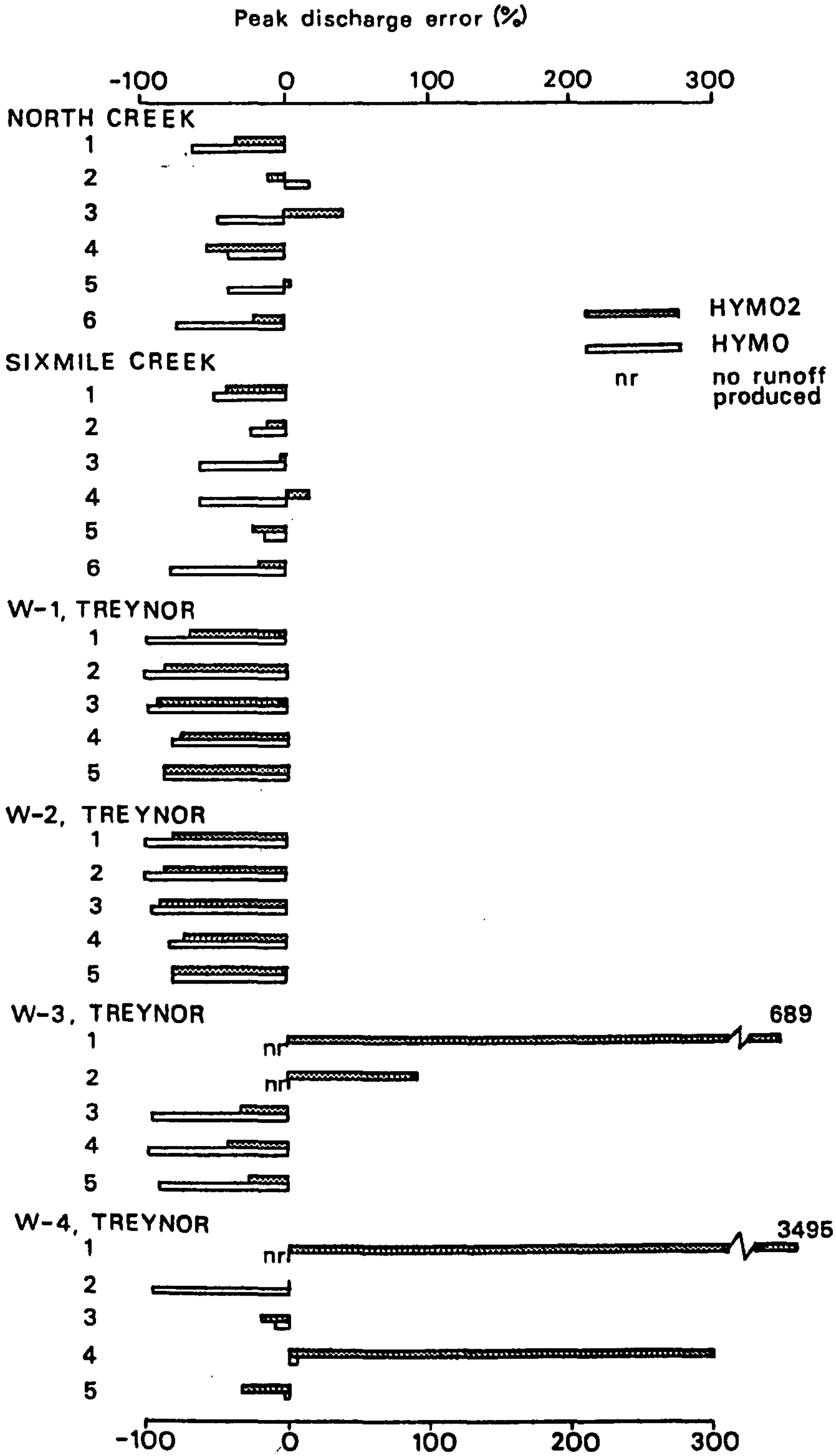


Figure 97 Comparison of the percentage peak discharge error of HYMO and HYMO2, for 32 experimental frames

predicts no runoff, the predicted peak discharge provided by HYMO2 is also greatly in error. For the North Creek and Sixmile Creek, HYMO only provides better predictions for one of the six storms in each of the catchments. These improvements are only of the order of 5% for the North Creek, and 2% for the Sixmile Creek. For W-1 and W-2, Treynor, Iowa, the modified model provides the better predictions for all but one storm, where both models provide the same prediction. For all storms applied to W-3, improvements are gained by the application of HYMO2. For all of these catchments therefore, application of HYMO2 is recommended. However, for three storms applied to W-4, Treynor, HYMO provides much more accurate peak discharge predictions and the choice of the most suitable model for prediction of peak discharge in this catchment is not as clear-cut.

Table 38 provides the percentage mean discharge error and the correlation coefficient of the predicted and measured hydrographs for a range of experimental frames (those indicated in figures 91 to 94) for HYMO and HYMO2. In all cases illustrated, except storm 4, Sixmile Creek, HYMO2 provides closer estimates of mean discharge. This improvement is quite significant in a number of cases. A closer linear association (although none are statistically significant), measured by the correlation coefficient, is also derived between the measured hydrograph and that predicted by HYMO2, than between the measured and that predicted by the original HYMO2 in all cases illustrated except W-3, storm 3, where the timing of the modified model predictions (figure 94A) has been demonstrated to be potentially inaccurate.

Stage 2: Comparison of model errors

Figure 98 illustrates the relationship between prediction error derived from HYMO and measured discharge for two experimental frames. The relationship illustrated in this figure exhibits two major differences to the relationship which was illustrated in figure 52 for HYMO2. Firstly, HYMO provides greater prediction error and secondly, very few negative errors (overpredictions) are produced. HYMO underpredicts the

Table 38: Comparison of percentage mean discharge error and correlation coefficient of predicted and measured hydrographs for a range of experimental frames for HYMO and HYMO2

		North Creek Storm 1	Sixmile Creek Storm 4	W-1 Iowa Storm 1	W-2 Iowa Storm 2	W-3 Iowa Storm 3	W-4 Iowa Storm 2
% mean discharge error	HYMO2	-0.4	50.0	14.0	-52.0	-17.0	78.0
	HYMO	-45.0	-43.0	-87.0	-97.0	-85.0	-93.0
Correlation coefficient	HYMO2	0.831	0.904	0.306	0.801	0.240	0.725
	HYMO	0.726	0.622	-0.284	0.184	0.304	-0.609

No correlation coefficient in this table is statistically significant at the 95% significance level.

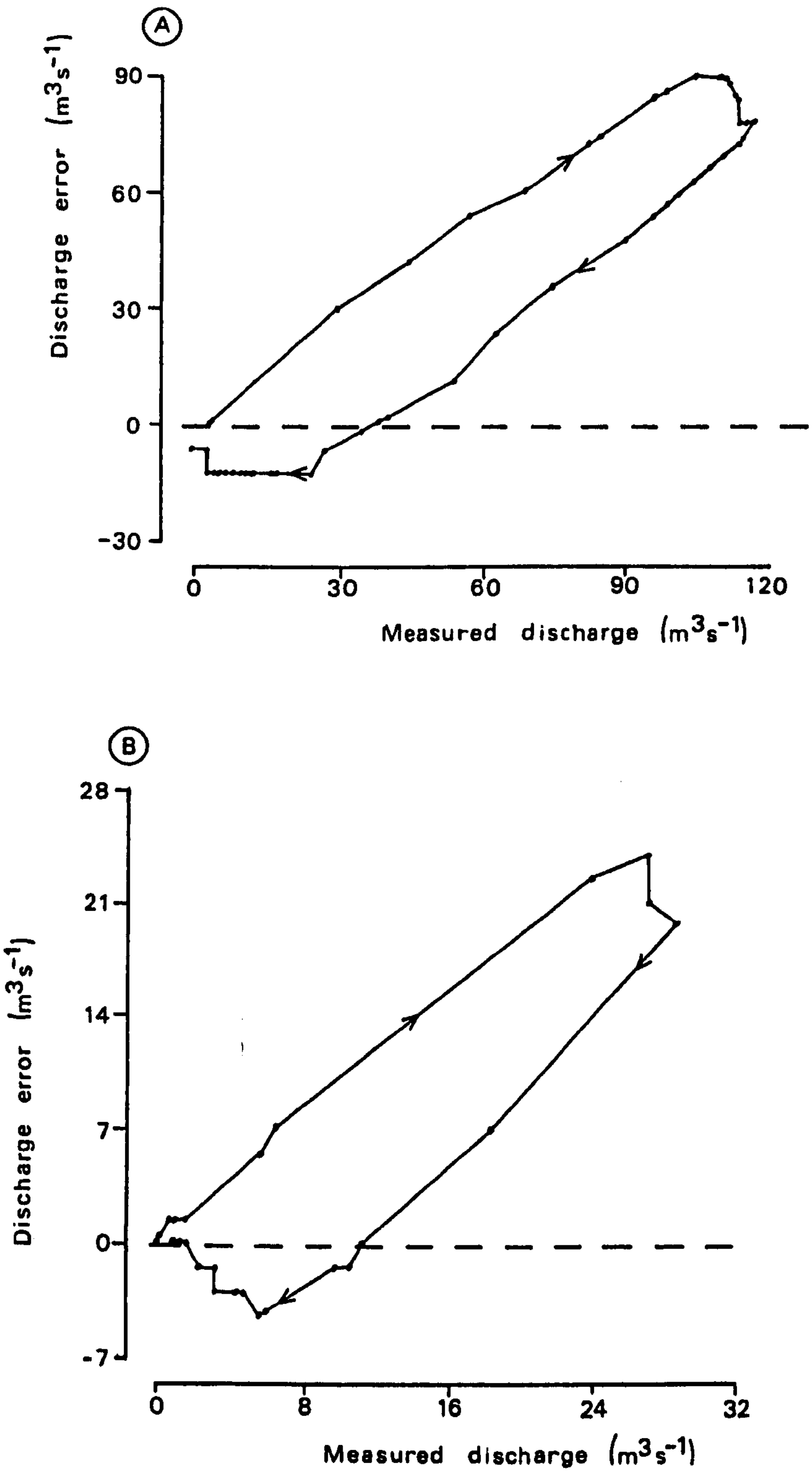


Figure 98 Relationship of prediction error derived from HYMO and measured discharge (A) Storm 1, 9 October 1964, North Creek (B) Storm 4, 3 November 1960, Sixmile Creek

measured discharge for the entire event hydrograph except for the smaller discharges experienced during the latter stages of the recession limb. The underprediction is greatest during the hydrograph rise and peak discharge and the overprediction tends towards zero error during the recession limb.

Figure 99 provides the autocorrelation functions for a selection of experimental frames. In comparison to HYMO2, HYMO exhibits very similar autocorrelation coefficients. The degree of autocorrelation in errors has therefore not been decreased by the introduction of the infiltration model.

Table 39 provides evidence that the mean error provided by HYMO2 is closer to zero than that derived from the original model, and that whilst HYMO2 does not consistently provide either negative or positive mean errors, HYMO does display a tendency to provide positive mean errors, i.e. a tendency to underpredict discharges throughout the hydrograph. HYMO2 also provides a lower standard deviation of errors than the original model. Errors from HYMO2 have a greater tendency to approximate a normal distribution than do errors derived from HYMO. HYMO2 therefore produces errors which tend to be slightly more randomly distributed than HYMO.

To summarize the points which have been made therefore, HYMO2, in comparison to HYMO, does provide:

1 A closer approximation to the form of the measured hydrograph.
2 A much improved time to peak discharge prediction.
3 Improved peak and mean discharge predictions for most experimental frames, but not for all. There are a number of frames where HYMO does provide significantly better predictions of peak discharge.
4 Smaller errors, with mean values which on the whole are closer to zero and have smaller standard deviations.
5 Provide discharge prediction error which has a greater tendency toward randomness.

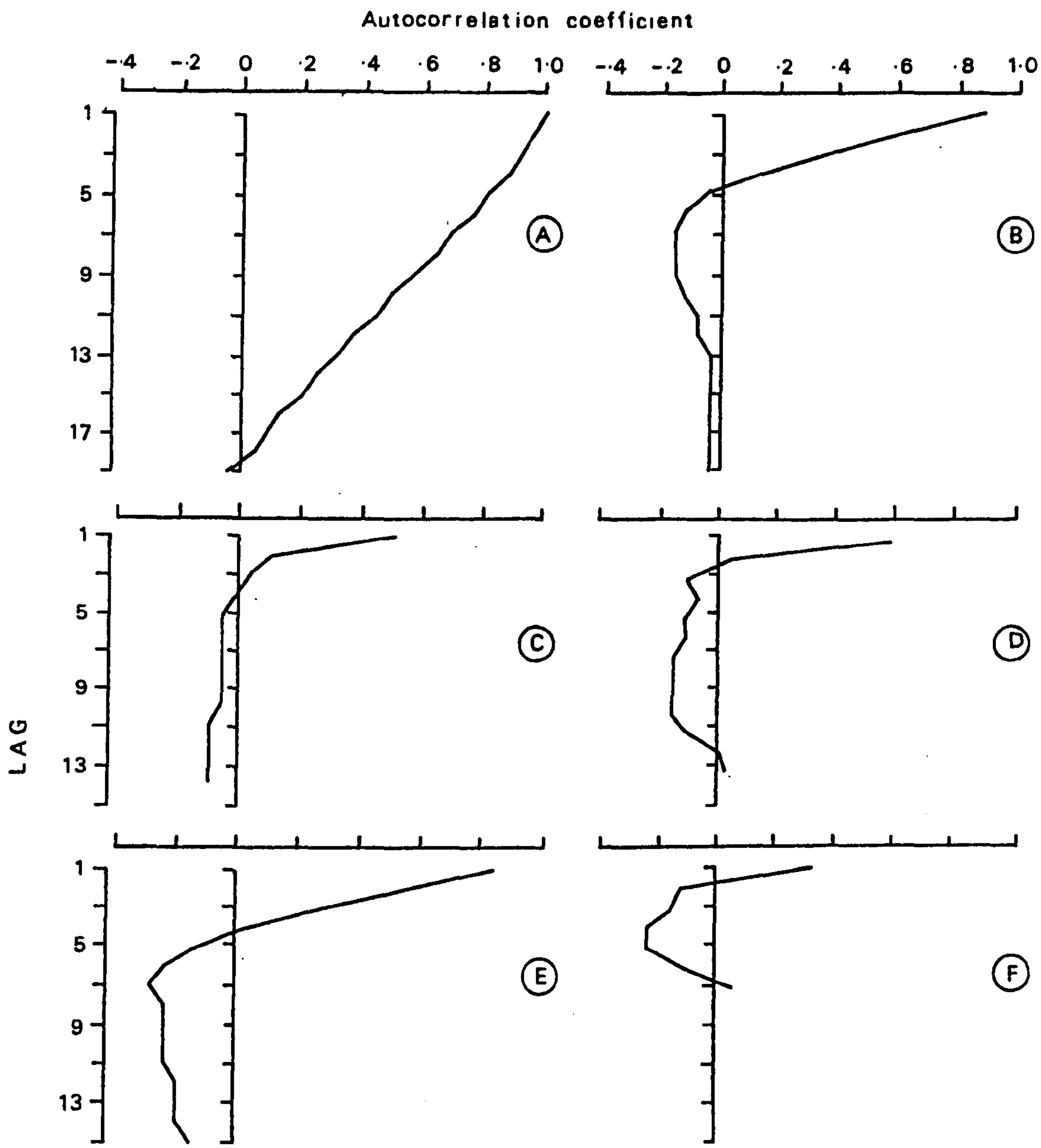


Figure 99 Autocorrelation coefficients for discharge error derived from HYMO for a range of catchment and storm conditions (A) Storm 1, 9 October 1962 ,North Creek (B) Storm 4, 3 November 1959, Sixmile Creek (C) Storm 1, 2 September 1970, W-1, Treynor (D) Storm 2, 26 July 1966, W-2, Treynor (E) Storm 3,14 July 1967, W-3, Treynor (F) Storm 2, 26 July 1966, W-4, Treynor

Table 39: Comparison of mean and one standard deviation of prediction error and correlation coefficient for normal probability plot for a range of experimental frames for HYMO and HYMO2

		North Creek Storm 1	Sixmile Creek Storm 4	W-1 Iowa Storm 1	W-2 Iowa Storm 2	W-3 Iowa Storm 3	W-4 Iowa Storm 2
Mean error (standard deviation) (m^2s^{-1})	HYMO2	-0.10 (24.6)	-1.39 (3.6)	-0.12 (2.2)	0.33 (1.0)	0.03 (0.2)	-0.24 (0.3)
	HYMO	13.10 (33.9)	1.18 (4.9)	0.78 (2.4)	0.62 (1.2)	0.14 (0.2)	0.34 (0.5)
Correlation coefficient (normal probability plot)	HYMO2	0.927	0.786	0.750	0.763	0.980	0.852
	HYMO	0.843	0.629	-0.646	0.775	0.834	-0.847

However, HYMO2 does not:

Reduce the autocorrelation coefficients for discharge prediction error.

7.4 Improvements in parameter sensitivity

The problems associated with the selection of ungauged catchment curve numbers have been stressed in section 7.2. These are particularly significant as the predictions of runoff are highly sensitive to the curve number value. This has been illustrated specifically by Hawkins (1975), in section 2.2, and in figure 12. This sensitivity has very serious implications for HYMO.

To illustrate the nature and significance of this sensitivity, the following series of figures is provided. Each is designed to illustrate the sensitivity of various hydrograph characteristics (peak discharge, time to peak, and error standard deviation), to a range of curve numbers. The examples are taken from the six storms applied to the North Creek catchment, Texas, and the six applied to the Sixmile Creek catchment, Arkansas.

Figure 100 illustrates the degree of sensitivity of peak discharge estimates. The nature of this sensitivity appears to be catchment dependent: it is greater for the North Creek, than for the Sixmile Creek. It also appears to be dependent upon the curve number value, being greater for a higher curve number. It is also interesting to note that for the North Creek, the sensitivity of peak discharge to an overestimate of the curve number which provides the best peak discharge prediction, is greater than to an associated underestimate. This assymetrical relationship is more clearly defined in figure 101, which provides the details of the sensitivity of percentage peak discharge error. A greater increase in error is associated with an overprediction of the curve number than with an underprediction.

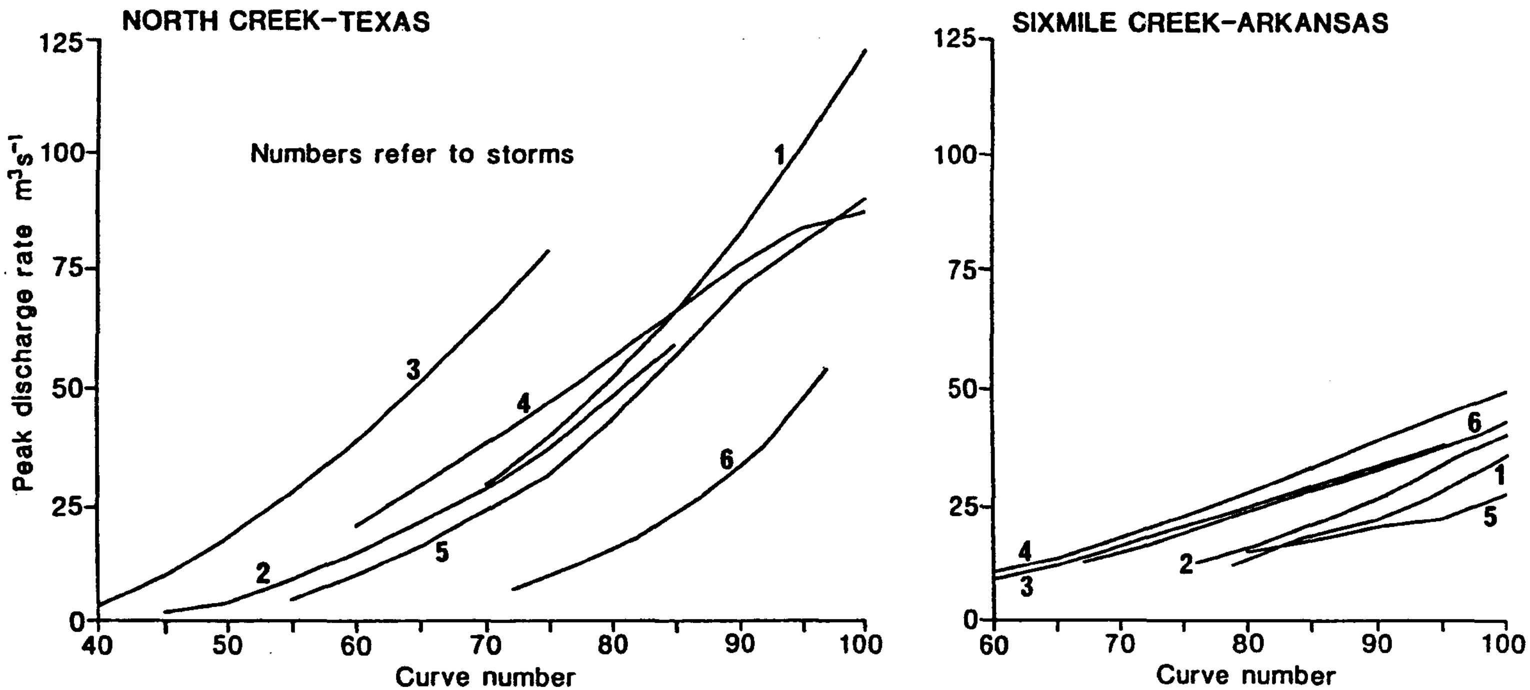


Figure 100 Sensitivity of peak discharge, predicted by HYMO, to the curve number value

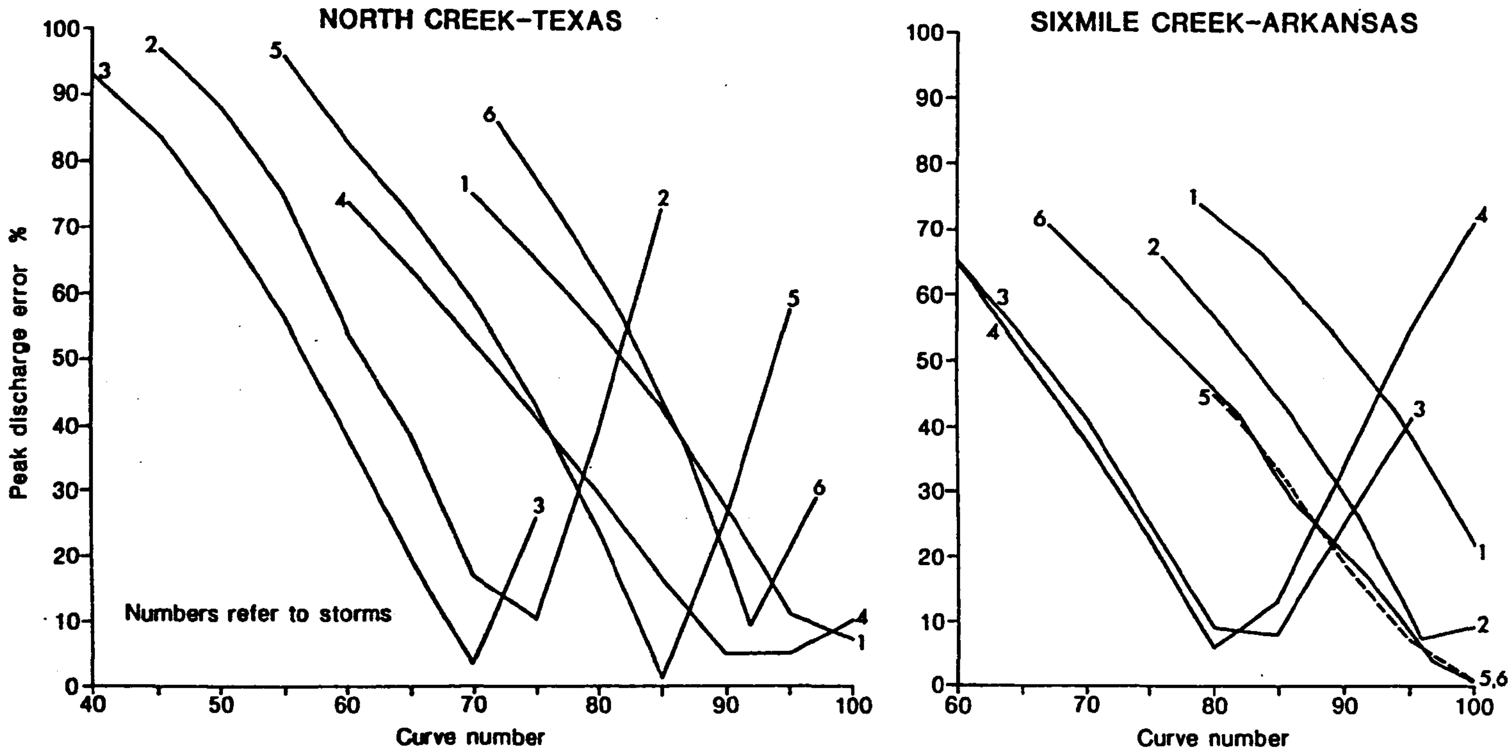


Figure 101 Sensitivity of percentage peak discharge error, provided by HYMO, to the curve number value

Figure 102 illustrates that the time to peak discharge predictions are not as sensitive to the curve number as are the peak dicharge predictions. Sensitivity here appears to vary according to storm characteristics. It is intersting to note the very low sensitivity for storm 3, a very short and intense storm, compared to the greater sensitivity to storm 2 which is of longer duration and more erratic nature. The degree of sensitivity does not appear to vary between catchments.

Finally, figure 103 illustrates the sensitivity of the error standard deviation to a range of curve number values. A greater sensitivity is displayed for the North Creek. The sensitivity does not vary significantly between storms for this catchment, but the assymmetrical nature of the relationship which was noted for the case of peak discharge predictions is also found here. A better fit of the predicted and measured hydrograph is achieved for the Sixmile Creek, and in association with this, a greater degree of stability of results is also attained.

In section 5.1, the sensitivity of the hydrograph predictions derived from HYMO2 to soil hydrological input parameters, and to choice of iteration period was examined for applications to the North Creek and Sixmile Creek. These results were presented in figures 31 to 34, and figures 37 to 40. It is to be suggested by reference to this information, that HYMO2 exhibits a lower degree of sensitivity to this input data than HYMO does to the curve number values.

Table 40 illustrates this suggestion, and has been derived from data relevant to storm 1, North Creek. In application of HYMO2, the Brakensiek and Rawls charts are used to derive soil data. In the absence of any other information, the centroid position on their charts, for each soil texture group, and an iteration period of 10 seconds can be assumed. Note therefore the low degree of sensitivity of the two hydrograph characteristics, and the error standard deviation, when this ungauged estimate of conditions is compared to the two other combinations of soil conditions which have been explained in section 5.1

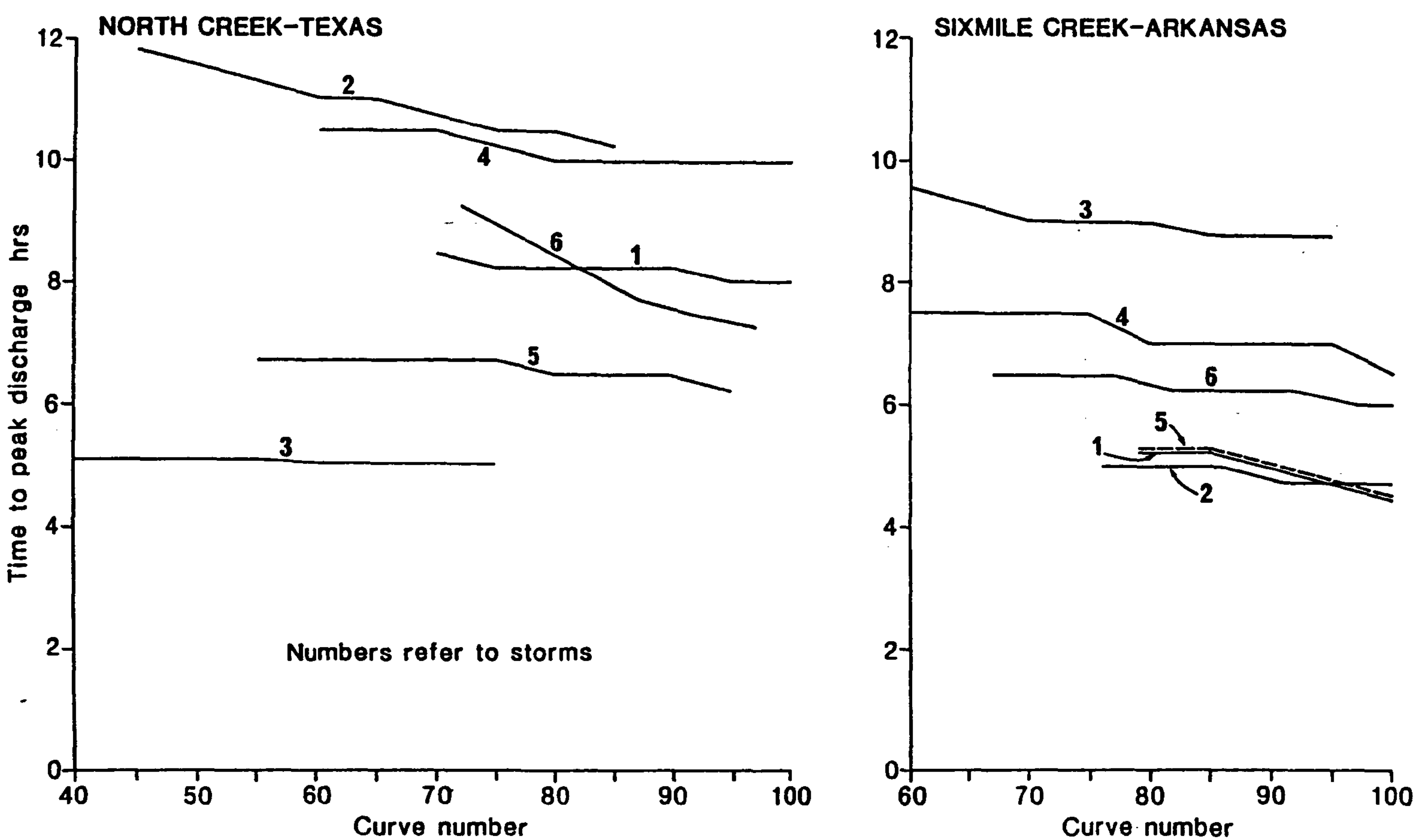
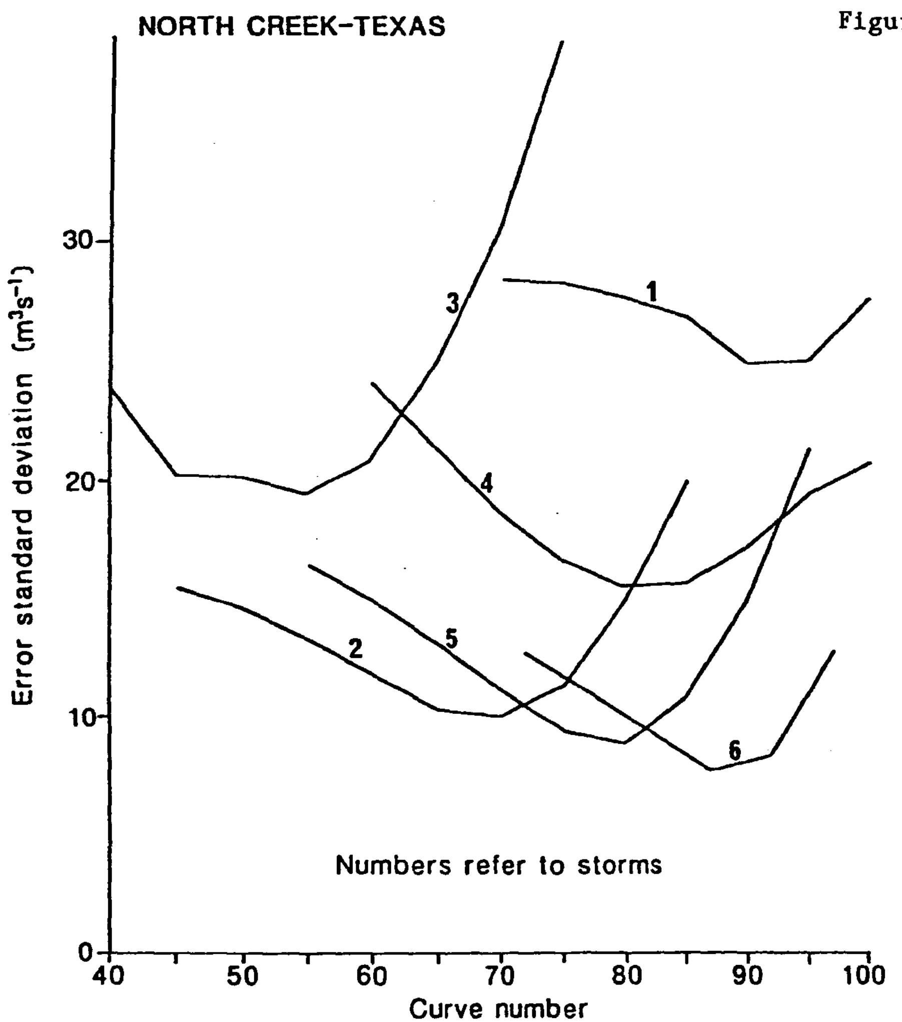


Figure 102 Sensitivity of time to peak discharge, predicted by HYMO, to the curve number value

Figure 103 Sensitivity of error standard deviation to the curve number value



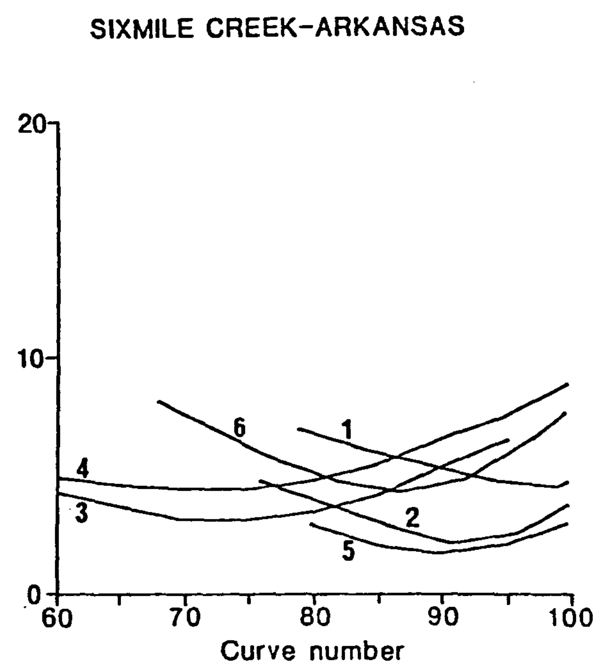


Table 40: Comparison of sensitivity of HYMO and HYMO2 for storm 1, 9 October 1962, North Creek

	Peak discharge ($m^3 s^{-1}$)	Time to peak discharge (hours)	Error standard deviation
HYMO			
CN = 81	53	8	31
CN = 76 (ungauged estimate)	43	8.5	70
CN = 71	30	8.5	38
HYMO2			
High % clay	65	8	26
Ungauged estimate	67	8	26
Combination conditions	76	8	25

Compare this low sensitivity to the much greater sensitivity of HYMO predictions to an overestimate and underestimate of five of the calibrated ungauged curve number. In addition, it will be recalled that due to the problems associated with the parameter estimation of the curve number model, that a miscalculation of 5 of the curve number is indeed a conservative estimate. Improvements in the sensitivity of HYMO2 in comparison to HYMO have therefore been provided.

It has been demonstrated in chapters 3 to 6, that HYMO2 represents a viable alternative to the original HYMO. This chapter has now established that HYMO2 represents a superior alternative. Improvements have been achieved in four fundamental areas: the conceptual basis of the model, parameter estimation, accuracy of hydrograph predictions, and in model sensitivity to input parameters.

8

Discussion

Mathematical hydrological modelling has been characterized by an emphasis on scientific model development rather than on model evaluation and the practical application of models to environmental and managerial issues. Mathematical hydrological models do have very important practical applications, yet there has been very little examination of the relationship of developments in scientific research programmes to practical problems. Consequently, this thesis has attempted to address these more practical issues. In particular, five specific issues in mathematical hydrological modelling are considered to be of interest and importance. These are the application of hydrological models to ungauged catchments, the development of operational hydrological models, the design and application of a detailed model evaluation strategy, the selection of a model structure which is most appropriate for the intended application, and the investigation of the implications of spatial variability upon modelling results.

In order to provide a basis for the discussion of these five issues, this thesis has documented the development of HYMO, and the evaluation and application of the modified version of this model, HYMO2. HYMO is a mathematical hydrological model which was developed by the USDA SCS to provide event flood forecasts and soil loss predictions for agricultural watersheds. An outline of the characteristics and structure of HYMO has been presented in section 2.1.

The development and evaluation of HYMO2 which has been undertaken is unique in its reference to these five issues, and as a result, HYMO2 exhibits the following characteristics:

1 HYMO2 has been designed specifically for application to the ungauged catchment. The ungauged catchment application is considered to be one of the ultimate aims of the application of mathematical hydrological models. However, the review of currently available ungauged catchment models which was reported in section 1.1, and summarized in figure 1 and tables 1 to 3 has revealed a number of severe problems and constraints with these models. A need can be identified for models which fulfil this application requirement.

2 HYMO2 has been developed in a form which is considered to be suitable to meet operational requirements. In the development of many mathematical models, far too little attention is paid to issues of logistics. Of course, there will always be a need for highly complex models in the interpretation and theoretical explanation of hydrological processes at a slope or catchment scale. However, many models which are specifically intended and labelled for practical and application purposes are clearly unsuitable for these conditions. They are far too complex and demanding in terms of data, computer resource requirements, and user experience, and are thus limited in application to, at best, a single and heavily instrumented catchment or, at worst, to a single hillslope segment. The nature of model parameter estimation and model execution can in addition often limit model application to technically competent personnel who have been closely involved in the design, development, and implementation of the model. There is a need for hydrological models which can be applied by a user with perhaps nonprofessional status, which are portable and hence applicable to a variety of catchments, and which can be implemented on a microcomputer system to execute in an acceptable period of time.

3 Close attention has been paid to a thorough evaluation of HYMO2. The modelling and simulation literature, both in hydrology and in other disciplines, contains prolific discussion on the importance of model evaluation. However, a great number of modelling exercises in hydrology can be heavily criticized for their inadequate attention to

this subject. A three stage model evaluation strategy (illustrated in figure 2) has been adopted in this modelling exercise. This involves a mathematical model evaluation (chapter 3), a computerized model verification (chapter 4), and an operational model validation (chapter 5).

4 Careful consideration has been paid to the selection of an appropriate model structure. Section 1.4 provided a discussion on the philosophical basis of any hydrological model, and emphasized the difficulty in establishing a methodology which is scientifically satisfactory, but which also remains operationally feasible. It is proposed here that a one dimensional, physically based infiltration model based on a numerical solution to the Richards equation has potential for practical application. Traditionally, physically based models have been regarded as more appropriate for scientific or research application.

5 An attempt has been made to incorporate, and thereby to examine, the effects of the spatial variability of catchment soils on the predictions provided by HYMO2. There is a good deal of field and modelling evidence of the importance of spatial variability in the catchment. The potential for the incorporation of variability into HYMO2 is severely constrained by the proposed ungauged and operational application which is intended here. The suitability of a Monte Carlo simulation methodology was evaluated in this particular modelling exercise.

This final chapter is divided into two sections. The first will summarize the major comments which have been made for each of these five issues and will review how the development of HYMO2 has served to illustrate many of these points. As a result of this work, the second section will outline a number of future research needs.

8.1 Review of major points

8.1.1 Application to the ungauged catchment

A discussion of the application of mathematical hydrological models to the ungauged catchment was undertaken in section 1.1 and the following two general points were made:

1 Very few hydrological models have been designed specifically for the ungauged catchment and yet this application is one of the most important in hydrological modelling. The ungauged catchment is one of the most challenging applications since it places severe constraints on a model due to the following three characteristics. Firstly, current or historical discharge records are not available and hence, calibration of model parameters is not feasible. Secondly, only very coarse, basic, and potentially inaccurate catchment data are available. Thirdly, relevant and accurate distributed precipitation records may not be available specifically for the catchment under consideration.

2 A review of ungauged catchment models has revealed that ungauged catchment models are available to predict various flood statistics (table 1), to provide flood forecasts (table 2), and to predict continuous discharge records (table 3). Many ungauged catchment models are calibrated parameter models and because discharge records are not available, three methods for parameter estimation have evolved. These methods vary in their degree of sophistication and reliability. Firstly, the models may be calibrated on a variety of gauged catchments, and from these results, tables are produced which are then used with little attention to the range of conditions for which they were derived. Secondly, parameters calibrated on a neighbouring gauged catchment may be extrapolated to a specific ungauged catchment which is considered to be hydrologically, geologically, and meteorologically similar. Thirdly, model parameters are calibrated using a number of gauged catchments. These parameters are then correlated to basin characteristics, such as

area, which are more easily measurable. These statistical relationships are then applied to the ungauged catchment. Unreliability and loss of forecast accuracy are associated with all three of these alternatives. It has been emphasized that there is no physical justification for the extrapolation of empirical relationships to the ungauged catchment. The dangers of transposing calibrated relationships to ungauged catchments have been stressed. In addition, it has also been noted that many ungauged catchment models demand catchment data which are of a greater quantity and higher quality than can realistically be associated with the ungauged catchment. To apply such models, either extensive field measurement programmes need to be established and thus the catchment becomes essentially gauged, or a large degree of hydrological intuition must be employed.

A need has therefore been identified to develop a model which can provide an event flood forecast for an ungauged catchment, upon which an acceptable level of confidence can be placed, which has physically based parameters, and which has reasonable data requirements.

This thesis has illustrated that such a model can be developed. HYMO is considered to be suitable in terms of data requirements (table 7) for application to the ungauged catchment. However, it has not been noted for accuracy in predictions. In section 2.2, attention was drawn to one particularly weak area of the model; the hydrological procedure which is used to compute catchment outflow hydrographs. In this procedure, catchment incremental runoff is derived from the application of the curve number model. This is a calibrated parameter model which has been developed by the USDA, SCS. It is simple, quick, and efficient to use, requires little data, is well established and accepted (in particular by United States Government agencies), and is provided with good documentation. However, the curve number method is not considered to be a suitable model for the prediction of incremental runoff in the ungauged catchment, since it was originally designed to provide estimates of daily total catchment runoff associated with daily rainfall totals. Consequently, in relation to the particular application needs of HYMO, it suffers certain conceptual and technical problems which have been fully outlined in section 2.2, and chapter 7.

Infiltration is one of the most important processes in catchment hydrology and it is essential that this is modelled correctly. Indeed, Woolhiser (1982) has emphasized that error in estimating infiltration is most serious in the simulation of catchment response. A review of potential alternative infiltration models which are currently available for predicting incremental runoff was therefore provided in section 2.3. The models which were considered included both exact (or physically based parameter) and approximate (or calibrated parameter) models. A one-dimensional, physically based parameter infiltration model, based on a numerical solution to the Richards equation was selected as being of a form suitable to replace the curve number method, and which in addition meets the ungauged requirements which are at issue in this application. The modified version of HYMO, referred to as HYMO2, is characterized by the replacement of the curve number model with the physically based parameter infiltration model.

The particular configuration of the infiltration model which has been utilized does not make unreasonable demands upon catchment data and indeed, to aid paramaterization, an empirical procedure has been presented which can provide estimates of the required soil hydrological properties. This empirical procedure has been derived from Brakensiek and Rawls (1983) and comprises a series of graphs and regression equations (figures 17 and 18) which can be used to derive the saturated hydraulic conductivity, saturated soil moisture content, and soil moisture characteristic curve of a soil type, from estimates of the percentage sand, clay, and organic matter.

The model evaluation which has been undertaken in this thesis has indicated that a reasonable level of accuracy can be placed upon the predictions which HYMO2, supplied with data generated from the Brakensiek and Rawls procedure, provides for a range of experimental frames. Chapter 7 has illustrated that HYMO2 provides significant conceptual, parameter estimation, prediction, and sensitivity improvements to the original HYMO.

The development of HYMO2 has therefore demonstrated the feasibility of deriving a mathematical model which has physically based parameters, but which can be applied to the ungauged catchment with acceptable accuracy levels. It has also provided evidence (in the context of the ungauged application) of the superiority of such physically based parameter models in comparison with calibrated parameter models.

8.1.2 Operational requirements

Section 1.2 has stressed that a selection of mathematical hydrological models must be available which are suitable for practical and routine use. Far too many models are documented as being suitable for routine application when they typically suffer excessive data requirements, require extensive computer resources, and demand detailed experience of the model by the user. Operational logistics place certain constraints upon the data which are available for model use, upon the computer resources which may be accessed, and upon the programming methodology which is adopted in model development. Subsections 1.2.1 and 1.2.2 have provided detailed discussion of these constraints, and the following two points were made:

1 An operational model should require data which can be collected and prepared in as small an amount of time as possible. There is a need to be able to assemble the information, to apply the model, and to provide results in real time. The data collection and preparation procedure should not be allowed to rely too heavily upon the experience of the user. Detailed guidelines for parameter estimation must be provided. Techniques should also be available for the user to generate suitable data for parameters which might not be commonly available for the ungauged catchment.

2 There is a requirement for mathematical hydrological models which are suitable to run effectively on a microcomputer system. This requirement constrains the physical size of the computer code which

is necessary to implement the program. In addition, it limits the complexity of the software. The program should also be designed to maintain a friendly interface between the user and program but most importantly, the software must be reliable.

The development of HYMO2 has been used to illustrate the feasibility of meeting these operational requirements, within the context of the ungauged catchment application.

The development of the original HYMO paid attention to some of these requirements. To apply HYMO, the user may select from a number of hydrological and model control procedures (figure 7), in order to develop flood forecasts for a catchment. These procedures allow outflow hydrographs to be computed for subbasin areas, to be added, and routed through both channel reaches and reservoirs. The procedures can be applied in any combination to meet specific catchment and user requirements. The model application is thus not confined to a particular catchment.

The modification of HYMO involved the replacement of the calibrated parameter curve number model with the physically based parameter infiltration model and has maintained, and attempted to improve upon, the operational capabilities of the original HYMO. HYMO2 does meet the data and computer requirements which have been discussed. It only takes of the order of three to six hours for the user to collect and to prepare the data which are necessary for application of HYMO2 to one subcatchment of up to 62 square km in area. Most of the model parameters are clearly defined, such as catchment area, elevation difference, and main channel length. Certain soil hydrological parameters may not always be available for the ungauged catchment, and an empirical procedure (derived from Brakensiek and Rawls, 1983) has been provided for parameter estimation in this case.

This thesis has suggested, based upon the range of applications which have been presented, that sufficient advice can be provided for the user to aid decisions such as the iteration period for solution of the infiltration equations, and for setting up the soil columns for the infiltration model. Careful consideration has been given to the form which this advice and information should take, and in section 6.2 it was suggested that this should be incorporated into an additional interactive program within HYMO2, rather than produced in the form of a written manual. This interactive program would provide help for the user in data preparation, entry, and checking. Indeed an attempt would be made to automate the data preparation procedure as far as possible, thus reducing the potential for user error. A possible structure for this interactive program is suggested in figure 68.

HYMO2 is also considered to be an operational model in terms of its computer requirements. The deterministic version of HYMO2 (written in Fortran 77) has been successfully ported and run on a microcomputer, the HP 9816. This microcomputer system comprises a 68000 microprocessor, 3/4 M byte of RAM, and 15 M byte of hard disc for program and data storage. The model will run on this configuration in a very reasonable period of time and is therefore considered to be suitable for realtime operational forecasting applications. HYMO2 is considered to be user friendly and the form of the original HYMO data file (figure 8) has been maintained. Currently, a seperate file is required for the infiltration model parameters but figure 68 suggests a methodology for improving the data entry for the infiltration model.

The infiltration model was written in Fortran 77, so as to be compatible with the HYMO code. The program has been written, as far as possible, according to the principles of structured programming. The software has been fully tested, and this issue is considered more fully in the following section.

Leimkühler (1982) has stressed that for a model to be successful as an operational model, it should not be complex and unexplainable. HYMO2, and particularly the infiltration model, is considered to be transparent. The overall model structure, every equation and parameter, are explainable to, and can be understood by, an external user.

8.1.3 Model evaluation

An examination of the role and importance of a thorough and well structured model evaluation was presented in section 1.3. In particular, the following three issues were raised:

1 There is a need for model evaluation as it is essential to have some estimate of the reliability of the discharge predictions which are derived for any catchment, but especially for the ungauged catchment.

2 A suitable model evaluation methodology will also serve to establish a model's suitability and relevance for a particular application. It is essential to judge a model's effective contribution, within the context of a particular application, thereby enabling the model to be accepted or rejected.

3 It is necessary to clarify, and to draw attention to, the potential, capabilities, and limitations of all mathematical hydrological models. If this information is not available, it becomes almost impossible for a model user to select the most appropriate model, and then to interpret the model results.

One of the main reasons why model evaluation has not been undertaken is that there is no clear idea of what exactly should be evaluated. A well structured and thorough, three stage model evaluation strategy (after Sargent, 1982) has been proposed and applied in this research programme. This strategy is unique in that emphasis is not laid solely upon a series of empirical comparisons, but also upon the application of a broader series of techniques (designed to test all phases of model construction), and upon a good research design.

The first stage of model evaluation is termed mathematical model validation. This is designed to be applied at a very early stage during model specification and initial development, and before large investments of time and money have been invested in the project. It is basically a subjective procedure, and involves a clarification of a model's assumptions and a discussion as to whether they are valid and suitable in the context of the application. A logical and internally consistent model structure must be established. The second stage is termed computer model verification. This seeks to demonstrate that there has been a correct translation of the mathematical model into computer code. It examines the accuracy of the computer program and the realism of the hydrological processes which it predicts. Thirdly, an operational validation is undertaken. This aims to establish that the mathematical model and computer implementation provide an acceptable representation of reality.

One essential feature of a model evaluation methodology is the research design. The assessment of a model must necessarily be made from a limited number of experimental frames. Therefore the selection of experimental frames will influence the utility of the comments and recommendations which can be made.

To illustrate the nature and potential of this proposed three stage model evaluation strategy, this thesis has documented a full evaluation of HYMO2.

The mathematical model validation (chapter 3) examined the question of whether HYMO2 represents an appropriate model for ungauged and operational application. The assumptions of the newly configured infiltration model for the derivation of incremental runoff, the assumptions of HYMO2 overall, and in particular, the assumptions of the dimensionless unit hydrograph procedure were stated clearly. The suitability of these assumptions, in the context of the proposed application, were then discussed.

It was suggested that the infiltration model does make reasonable assumptions in the context of the application. The very limited available data and computer resources, and an inexperienced user have constrained the complexity, and therefore the degree of realism, which the model can attain. Certainly, there are examples of more complex physically based infiltration models, which incorporate flow in more than one dimension, hysteresis, and soil crusting for example. This thesis argues that it is neither conceptually nor technically acceptable to apply these complex models to ungauged situations where suitable data are not available and hence where a very large number of unknowns are introduced.

It was emphasized that a very limited number of catchment hydrological processes are incorporated into HYMO2. More complete and realistic catchment hydrological models have been developed, and discussed in section 3.2, but these models are not suitable as they do not meet the requirements of the ungauged and operational application.

The dimensionless unit hydrograph procedured was identified as one potential source of model error due to its lumped nature and to the assumptions of linearity and time invariance which it makes. The unit hydrograph model is consistent with the ungauged and operational application and was therefore retained for the initial analysis of HYMO2. The evaluation of HYMO2 has subsequently identified the unit hydrograph procedure as a potential area for future attention and improvement.

The discussion of the validity of the mathematical model has stressed that the ungauged and operational application restricts the model complexity and that to date, only empirical models have been used successfully in the context of this application. This thesis has documented the replacement of the simple curve number runoff model with a more complex and more realistic physically based infiltration model It has demonstrated that such a model does have potential for improved prediction accuracy in the context of this application but that there is a limit to the degree of realism which can be achieved.

The computerized model verification (chapter 4) investigated three specific issues concerning the computer implementation of the mathematical infiltration model. Firstly, it was established that the infiltration algorithm operates according to theory for a range of simple soil conditions. In particular, the development of relative saturation at 10 cm depth, the net soil moisture fluxes for a range of storm and soil conditions, and the numerical derivation of the hydraulic function were demonstrated to be physically realistic.

Secondly, a stochastic sensitivity analysis was undertaken which established that a realistic infiltration model had been formulated. The infiltration model was demonstrated to be sufficiently sensitive to represent the variation of infiltration behaviour associated with soil differences. The sensitivity analysis was designed to examine the relative significance of error in the specification of each of the five hydrological parameters: saturated hydraulic conductivity, saturated soil moisture content, the soil moisture characteristic curve, initial moisture content, and detention capacity. HYMO2 was shown to be most sensitive to saturated hydraulic conductivity, and then to the soil moisture characteristic curve, the initial moisture content, saturated soil moisture content, and is least sensitive to detention capacity. The variability of model predictions was demonstrated to increase firstly in association with an increase in the variability of the input parameters, and secondly for storms of low intensity and long duration. Peak discharge was seen to be far more sensitive to error in the input parameters than time to peak discharge. As the magnitude of variation of the input parameters was increased, a decrease in the predicted mean values of runoff, peak discharge and time to peak discharge were recorded.

The sensitivity analysis has indicated that the infiltration model is a feasible alternative to the curve number method for the prediction of incremental runoff in the context of the ungauged application.

The third issue which the computer model verification has examined is the accuracy of the explicit finite difference method which provides an approximate solution to the Richards equation for one dimensional infiltration. The magnitude of the numerical error is indicated by the value of (BAL) (equation 48). Negligible errors were experienced for the range of catchment and storm conditions which have been used in the sensitivity analysis. This method of solution was therefore accepted as appropriate.

It must be stressed that a complete computer model verification has not been, and indeed could not be, undertaken. The results of the computer model verification are very promising, but possible undetected software errors must be an expectation of a user, and model predictions must therefore not be used blindly. The behaviour of the infiltration model for a good range of hypothetical conditions has been examined, and has indicated good reason to pursue further model evaluation for actual catchments. Thus data for a range of catchments were collected and the investigation of model operation for more complex catchment conditions was undertaken.

The operational validation (chapter 5) provided an assessment of the performance of HYMO2. The performance of the model was considered strictly in terms of its ability to replicate a measured hydrograph. Data for the North Creek, Texas and the Sixmile Creek, Arkansas, were utilized primarily and the following three issues were examined.

Firstly, the utility of the Brakensiek and Rawls empirically derived soil hydrological data, and the effect of the choice of iteration period for solution of the infiltration equation were examined. It was determined that the empirically derived parameters do indeed provide acceptable predictions for a range of storms applied to the North Creek and Sixmile Creek. The discharge predictions which HYMO2 provides were demonstrated to be sensitive to the percentage sand, percentage clay, and iteration period which were selected. However, this sensitivity is not as great as the sensitivity which the original HYMO displayed to the curve number value, and it is considered that, in the context of the ungauged catchment, default values for percentage sand, percentage clay, and iteration period, could be determined for the operational use of these parameters. Indeed in the application of HYMO to five catchments in Vermont and Iowa, which has subsequently been undertaken, the centroid value for each soil texture group, and an iteration period of 10 seconds were assumed for all applications, and forecasts were acceptable in many cases.

Secondly, a number of comparsions between measured and calculated hydrographs were documented. The importance of the use of a range of numerical and graphical methods of comparison has been stressed in order to achieve a good assessment of model performance. A systematic two stage methodology for comparision has been proposed (figure 41), which initially compares the two hydrographs, but which then proceeds to examine the prediction error. Model improvements can not be achieved until the nature of the error has been identified thus leading to suggestions of a possible source. Overall, the prediction which HYMO2 provides for the North Creek, and the Sixmile Creek, are considered to be acceptable. Prediction of the overall hydrograph shape is good, and the prediction of the timing of the peak discharge is particularly good. There is however, a tendency to underpredict the measured peak discharge. The highly peaked form of the measured hydrograph is also not well predicted. Overall, closer predictions are derived for the Sixmile Creek than for the North Creek. A consistent and systematic pattern of discharge prediction errors has been noted. The errors are not randomly distributed but a pattern of overprediction during the early period of hydrograph development, underprediction of peak discharge, and overprediction of the latter stages of the recession, occurs during many experimental frames. This pattern is not confined to one particular storm type or catchment although the absolute magnitude of the errors does vary and is greater for the North Creek. The errors are demonstrated to exhibit autocorrelation, they are not normally distributed, error means are not zero, and especially for the North Creek, quite wide standard deviations occur.

This prediction error is not considered to be related to data error, due to its consistency and similarity in form between storm and catchment types. A deficiency in the model structure is therefore considered to be responsible, and the unit hydrograph procedure is considered to be a very likely source of this error.

Thirdly, the operational validation examined an application of the stochastic version of the infiltration model in HYMO2. This has provided quite disappointing results. The details of applications to just two storms in the North Creek have been documented in this thesis and for these storms the stochastic model does not provide improvements in model predictions. This particular application of HYMO2 will be discussed further in section 8.1.5.

Further applications of HYMO2 were reported in chapter 6, and in the context of this range of catchment conditions, several aspects of the model operation were evaluated. A series of comparisons between the measured and calculated hydrographs was provided for a number of storms applied to W-2, North Danville, Vermont and W-1, W-2, W-3, and W-4, Treynor, Iowa. These are all small catchments and were chosen in order that the modified hydrograph computation procedure of HYMO2 be fully verified. The predictions which HYMO2 provided were not considered to be acceptable for W-2, North Danville, Vermont. In this catchment, a good proportion of storm runoff follows subsurface paths to the catchment outlet, and the application of HYMO2 to these conditions is not considered to be appropriate. However, for the four catchments near Treynor, Iowa, a range of more acceptable predictions was produced. Again, there is a tendency for underprediction of discharge although in many cases, the overall form and especially the timing of peak discharge is predicted very well. A systematic form of error is produced, and the form very closely resembles that noted for the North Creek and Sixmile Creek: errors exhibit autocorrelation, they are not normally distributed and have mean values which differ from zero. This provides further evidence for a structural deficiency in HYMO2, and thus of the unsuitability of the unit hydrograph procedure in HYMO2.

Information from these catchments was also used to illustrate that the predicted infiltration behaviour for a number of soils is realistic, that negligible numerical errors are associated with the finite difference method, and that the computer requirements of the model are reasonable. In a summary of applications, it is considered that very good predictions are provided for time to peak estimates. Indeed it is considered that there is very little practical significance of disparities between the measured and calculated time to peak discharge. The prediction of peak discharge and of the overall form of the hydrograph are considered to be best for peak discharge events of between 20 and 65 $m^3 s^{-1}$. However, rather than this being a function of the size of the event, it is considered to more likely be a function of the particular catchment location. The better predictions of HYMO2 are derived for the Sixmile Creek and the North Creek. These are larger catchments, and therefore provide larger peak discharges but they are located in those States which provided the data for calibration of the dimensionless unit hydrograph. It is reasonable to suggest therefore that the particular form of the dimensionless unit hydrograph which is used by HYMO2 is not as suitable for catchments in Iowa or Vermont, as it is for catchments located in the area for which calibration has been undertaken. This supplies additional evidence to support the further exploration of a range of calibrated unit hydrographs in a future improvement to HYMO2.

This application of the three stage model evaluation strategy to HYMO2 has illustrated that there are a range of tests which can be applied both during model development, to provide support for continued investments of time and finance in the research programme, and after model development, to provide potential users of the model with information concerning its capabilities and limitations. The model evaluation of HYMO2 has been sufficiently comprehensive to provide conceptual and empirical justification of HYMO2 as an acceptable mathematical hydrological model for operational application to the ungauged catchment.

8.1.4 Model structure

A firm conceptual basis for the selection of all mathematical hydrological models is considered to be essential. All mathematical hydrological models should, within the context of the application, be hydrologically and logically sound. However, section 1.3 has emphasized that most scientifically and conceptually satisfactory models are physically based and have traditionally been confined to scientific application. Technical difficulties such as large data and computer requirements, and the experience which is required by the operator have excluded their use for practical applications. Models which have been used for practical problems contain many simplifications and have mainly comprised empirical models. Figure 3 outlined the differences in the role and hence the characteristics of these two types of models. It is difficult therefore to reconcile a methodology which is scientifically acceptable, but which also remains applicable to the ungauged catchment, and is operationally feasible.

This thesis has proposed that certain elements and developments of physically based scientific models can serve a useful purpose in practical application. State of the art models will not always be the most suitable, reliable, and credible models for this application, and as Body (1975) has stressed, the models which a practitioner uses will necessarily lag behind current research. It is necessary that complex scientific models be refined and developed into simpler forms so that they may be presented as viable design tools. However, very little effort has been directed towards this need.

In this thesis, the suitability of physically based parameter models for application to the ungauged catchment has been emphasized and the potential of using a simplified, but physically based model has been demonstrated. A one-dimensional infiltration model has been demonstrated as a feasible and a superior alternative to the simpler, calibrated parameter curve number model for the prediction of incremental runoff in a catchment area. Simplifications in terms of processes, dimensions, and numerical solution have been made to ensure that the model is consistent with ungauged and operational requirements. Chapter 7 has illustrated that this physically based model does provide more acceptable predictions than the empirical curve number model. In fact four improvements have been outlined.

Firstly, the physically based alternative is conceptually superior to the original empirical procedure. The infiltration model, based on the Richards equation is a more appropriate model for predicting incremental runoff than the curve number model. It has been stressed that the curve number model has been applied out of context, and that it was originally conceived merely as an index of daily runoff potential. The infiltration model is not a calibrated parameter model, it is physically based and therefore is more suitable for an ungauged catchment situation.

Secondly, one of the arguments which has been raised against the use of physically based models in practical application has been the problem of providing model parameter values. However, application of both HYMO and HYMO2 has illustrated that there is not a great increase in effort associated with parameter estimation for the infiltration model, compared to the curve number method. Evidence which supports the suitability of using empirical procedures for the derivation of soil hydrological parameters has also been provided. An interactive computer program to aid parameter estimation could provide enormous potential for the use of more complex physically based parameter models for operational procedures.

Thirdly, it has been illustrated for a range of experimental frames, that certain improvements in prediction accuracy have been achieved by the replacement of the curve number model with the infiltration model.

Fourthly, improvements in parameter sensitivity have been achieved by the replacement of the curve number model with the infiltration model.

It has been widely assumed in the hydrological modelling literature that physically based models are conceptually superior and therefore preferable to empirical and simpler models. This thesis has consequently argued that to provide prediction and parameter estimation improvements to practical and operational models, which have traditionally been empirical and therefore calibrated, elements of physically based models should be introduced. Indeed this proposition has been supported by the improvements to HYMO which were derived by the replacement of a calibrated curve number model by a physically based parameter infiltration model for the prediction of incremental runoff.

8.1.5 Spatial variability

It has been established in section 1.5 that there is indeed a good deal of empirical evidence of within-catchment variability in both soil and precipitation characteritics. This variability does have implications for the spatial and temporal operation of hydrological processes and thus it is logical that it be considered in the transformation of rainfall into runoff. Methodologies must therefore be designed to incorporate this variability into the structure of mathematical hydrological models.

A review of such methodologies has been provided in section 1.5 and summarized in figure 4. Examples have been provided of lumped models in which no variability of hydrological properties or processes within the catchment is considered, and where model parameters consequently represent spatial averages. These models can be heavily criticized for such simplifications. However, they have survived due to their expediency, and because experience has proved their suitability for a range of applications. Semi-lumped models incorporate a small degree of variability by the subdivision of the catchment area into smaller units which are then regarded as internally homogeneous. Fully distributed models are more complex and demanding in terms of data and computer requirements. There are two types of fully distributed model: probability and geometrically distributed. Probability distributed models disregard the relative location of catchment parameters but incorporate a measure of the statistical nature of the variability of catchment parameters. Various types of probability distributed models have been identified, classified according to the nature of their description of catchment variability: whether it is in terms of conventional statistics, geostatistics, or scaling theory. Geometrically distributed models incorporate deterministic variation of model parameters in the catchment and are based on the assumption that the relative location of parameters in the catchment is essential. These geometrically distributed models are typically physically based, and parameter values are therefore required to be distributed over three-dimensional space. The catchment may be divided into a grid, or a cascade of planes, depending upon the degree of model complexity. These models are the most demanding in terms of data and involve complex numerical solutions. Consequently, a family of semi-distributed models has evolved. Geometrically distributed models have been simplified and aggregated to produce models more suitable for practical application.

HYMO is a semi-lumped model. HYMO2 remains basically semi-lumped, but incorporates two additional ways in which to model the variability within a subcatchments are. Firstly, any number of soil types can be used in the infiltration calculation. The infiltration behaviour of each major soil type can be simulated and the relative contribution of each to total runoff is weighted according to the percentage area which the soil occupies in the subcatchment. The limit to the number of soil types will depend upon the data which are available, and upon the response time which is required for model predictions.

The second method of modelling the variability within a subcatchment area is to include a stochastic methodology. The constraint of the ungauged and operational application have necessarily limited the choice of an additional methodology which could be utilized to further include the effects of variability. However, within the context of the proposed application the suitability of a stochastic methodology, based upon the description of catchment variability in terms of conventional statistics: a probability density function, mean, and standard deviation has also been evaluated. Subsection 2.4.4 has provided a description of the implementation of a Monte Carlo methodology which incorporates the variability of the five soil hydrological parameters: saturated hydraulic conductivity, saturated soil moisture content, the soil moisture characteristic curve, detention capacity, and initial soil moisture content. Section 5.3 has provided two examples of the application of this stochastic methodology to two storms applied to the North Creek, Texas.

Measures of the variability of the five soil hydrological properties were derived from the literature and do not therefore correspond specifically to the soil type in the catchment, but more generally to a soil texture classification. Consequently, they may not be totally representative of the conditions which existed in the North Creek at the time of the two storms. However, in the applications reported here, and in further applications reported in Anderson and Howes (in press), the variability which was incorporated had the net effect of reducing the discharge predictions at each time interval. The tendency of the deterministic version of HYMO2 to underpredict discharges which has been noted, and the reduction of discharge prediction which results from the stochastic application mean that the predictions of the stochastic model are worse than the deterministic. This is illustrated very clearly in table 31.

It is possible that the Monte Carlo methodology which has been implemented is not suitable for including variability in the model. All five soil hydrological parameters are simultaneously varied, and independency is assumed. However, certain checks must be made to ensure physical realism and consistency of randomly generated parameter values. These checks appear to act to bring down discharge predictions. Certainly in this application, where performance of a model is judged merely by its ability to match the measured hydrograph, the deterministic model does supply better results and at a much reduced data and computer cost.

8.2 Future research needs

Based on the comments made on the five issues upon which this thesis is based, four areas for future research can be identified and are now discussed in this final section. These four areas for research are: further improvements to HYMO2, developments in modelling approaches, applications of remotely sensed data in hydrological modelling, and the potential of fifth generation computer technology for improving modelling techniques.

8.2.1 HYMO2: areas for further development and evaluation

A series of comparisons of hydrographs predicted by HYMO2 to measured values, for a range of experimental frames, has identified a need to improve, or to provide a replacement for, the empirical dimensionless unit hydrograph procedure which is used to transform runoff into a catchment outflow hydrograph. To be consistent with the replacement of the curve number model by a physically based parameter infiltration model, recommendations can be made for the examination of the potential of physically based parameter models for the routing of overland flow. However, the solution of the overland flow equations has probably not yet attained the stage of simplification required to allow an uncalibrated soluation as has been the case with the solution of the Richards equation. It is possible that, in the context of the ungauged catchment, a unit hydrograph is the only suitable method by which incremental runoff can be transformed into the stream hydrograph response. In this case, the dimensionless unit hydrograph might require a more extensive data base for calibration, or possibly, a range of dimensionless unit hydrographs should be made available which vary with catchment or storm condition. The user could then select the most appropriate unit hydrograph equation for the particular application requirements.

The evaluation of HYMO2 which has been undertaken in this research programme has concentrated solely upon an evaluation of the modified hydrograph computation procedure. It has therefore only referenced single subcatchment areas and no chanel routing has been performed. In the context of the ungauged catchment, the utility of the channel and reservoir routing procedures in HYMO2 must also be examined. Williams (1975) claimed that the Variable Storage Coefficient method suffers one serious fault: peak discharge may increase as the flood wave moves downstream. This is evident especially when routing through reaches with little storage (channels with no flood plain). He suggests that a more accurate solution to the routing problem would be provided by the Variable Travel Time method. This is slightly more complex than the Variable Storage Coefficient in that the time interval varies according to the travel time relationship. A selection of much larger catchments is therefore required which can be subdivided into a number of subcatchment areas, and the routing procedures examined.

The validity of the empirical procedure for deriving soil hydrological information (Brakensiek and Rawls, 1983) has been established for a range of American catchments. This procedure has been derived from a data base containing American soils and because of the sensitivity of the infiltration model to soil hydrological parameters, its utility should be investigated for soils in other countries.

8.2.2 Model structure: the need for lateral thinking

This thesis has provided certain evidence which reinforces the popular belief in hydrological modelling that physically based models provide certain conceptual and prediction improvements to empirical models. Based upon this evidence, it is therefore suggested that one very profitable area for research activity could be based upon an evaluation of the potential of other physically based models for practical application; for example, subsection 8.2.1 has suggested physically based routing of overland flow as one possible area for research to provide further improvements to HYMO2.

However, it is also important to appreciate that physically based models do themselves suffer certain fundamental conceptual problems and should not be regarded as a panacea for all hydrological modelling ailments. It has certainly not been the case that improved predictions are always associated with the application of complex models in preference to simpler, empirical models.

This thesis argues that there are three conceptual problems with physically based models:

1 An inadequate or unobtainable theoretical description of hydrological processes

It is essential that a physically based model is founded on sound theoretical principles. Klemeš (1983) has emphasized that it is not sufficient that a model should contain a few well established concepts if at the same time it contains a number which are vague and questionable. There are many aspects of hydrological processes for which there exist qualitative physical description, but due to the complexity and variability of reality, quantitative description of every process, at every point, and in mathematical terms is not yet available.

Vansteenkiste and Spriet (1982) considered that a similar condition of unsatisfactory theoretical description exists for biological systems, and that this is one cause of some mathematical modelling exercises in biology being considered unsatisfactory. It is interesting to consider their argument in that a similar claim can also be made for hydrological modelling. Figure 104 is based upon a figure which they produced, and illustrates all scientific investigation as beginning with observations and progressing iteratively, rather than consecutively, to a stage where general theory can be developed. Mathematical modelling may be attempted at any of these evolutionary stages, but as suggested by the figure, the models derived from each route are associated with varying degrees of generality and validity. Biological systems are not considered to be sufficiently well defined to allow modelling to be approached via route I. This could be considered to be the case for theoretical hydrology. In hydrology, mathematical models are typically approached via routes II and III.

Proceeding from this observation, it can be suggested that ′rigorous′ general theories cannot be developed in hydrology. Vansteenkiste and Spreit (1982) examined a number of properties of biological systems which they considered inhibited the development of such general theory and many of these are also characteristic of hydrological systems: the natural processes are intricate and complex, it is impossible to define system boundaries, there are scale problems (a feature to which attention will be turned later), and the system is not easily accessible (it is difficult to get measurements due to inseparable processes, measurement error, and inherent variability). It is reasonable to consider that the nature of the phenomenon may set the upper limit to

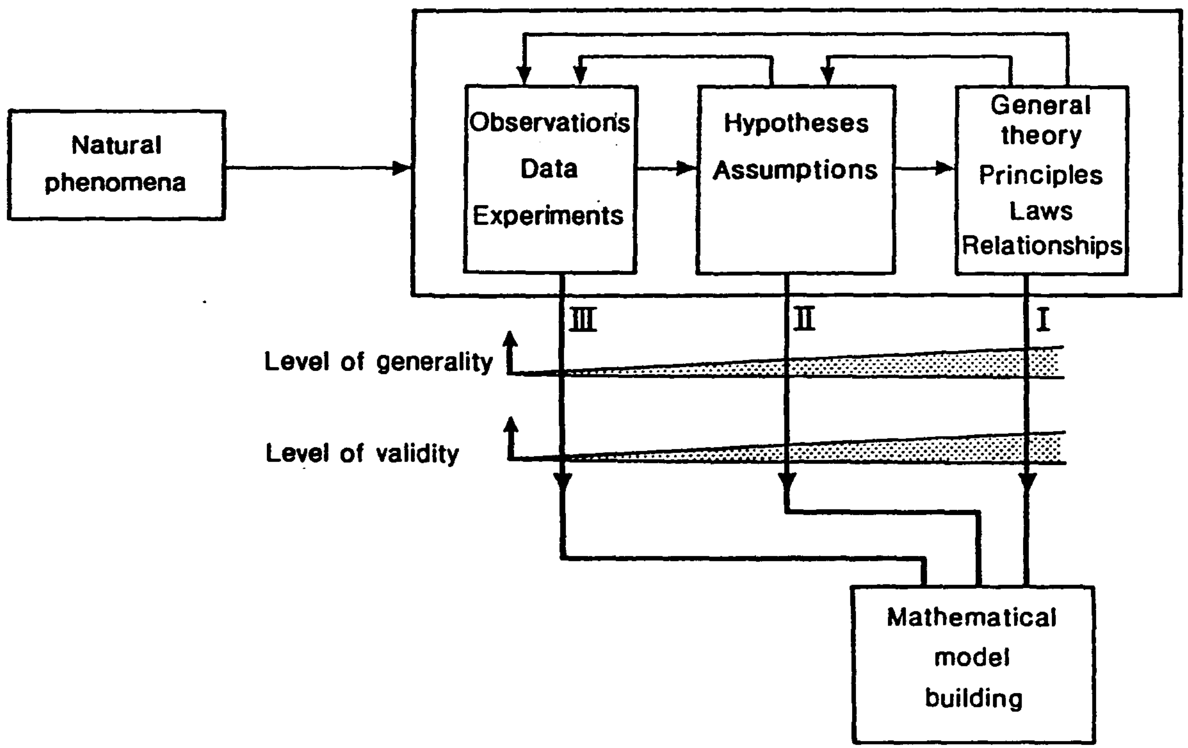


Figure 104 The progression of scientific investigation and three possible routes for mathematical model building (adapted from Vansteenkiste and Spriet, 1982, figure 1)

the degree of modelling which is possible. Indeed, Blackie and Eeles (1985) considered that the natural system is so complex and large that a complete representation will never be attained. For example, in hydrology, Woolhiser (1982) defined overland flow as a thin sheet flow which occurs before surface features cause channeling. This very rarely occurs in the field as flow surfaces are not planar. Overland flow equations most often describe flow conditions which do not occur in reality. There is no unique set of physical laws for describing the movement of water.

Mar (1974), Vansteenkiste and Spriet (1982), and Cellier (1982) have all drawn attention to the fact that the procedures for mathematical modelling were designed for use in physical deterministic systems, or in the 'hard' sciences. These are clearly defined systems, in which the general theoretical principles are well known, for example, electrical network systems, weapon systems, or industrial systems. Little procedural information exists for mathematical modelling in the environmental system. All these authors stressed that it may be necessary to consider alternative modelling strategies and techniques for use in these conditions.

2 The assumption of determinstic hydrological processes

Implicit in any physically based model is the assumption that natural hydrological processes are deterministic. Both Yevjevich (1974) and Klemeš (1978) have interpreted hydrological processes to be either purely or partly stochastic and consider the search for exact deterministic explanation to be inappropriate. As Klemeš (1978) stated, such is our deterministic view of the world that we attribute our inability to apply physically based models successfully to natural hydrological systems to failure in our theoretical basis and to an inability to determine the correct parameter values. Few would consider that this failing may be due to randomness, an inherent feature of the hydrological system. Yevjevich (1974) has argued with the assumption in current deterministic hydrology that the ratio of signal, which can be explained by physical laws, to unexplained noise, will increase in time, presumably as hydrology moves iteratively to the right in figure 104.

He argued that deterministic models are not applicable to the natural environment and cannnot hope to succeed. As Amorocho (1967, p 862) pointed out, "...it is futile to attempt to step beyond the limits of the physically possible by carrying the banner of strict determinism against all odds".

3 An inadequate consideration of scale

The consideration of scale is very important in mathematical hydrological modelling. This issue has been raised by Klemeš (1978, 1983) and Dooge (1984). It is important to appreciate that depending on the scale at which an environmental system is viewed, there are different sets of laws which operate. Scale is a function of the real system and cannot be imposed upon the system by the scientist.

In hydrology, deterministic physical processes have been formulated at the small scale. They have been validated for this scale with data from the laboratory or the runoff plot scale. In moving to applications at the catchment scale, it has been normal to aggregate these component processes. In practice this disregards the very continuity of the real system, and there has been very little work concerned with modelling the complex interactions between the component processes. By increasing the scale of application of these models, difficulty has been experienced in deriving parameter values, which originally referred to points in the field, and which now have to be applied to areas. This has necessitated the calibration of these models to derive parameters relevant to the scale of interest and thereby defeating the object of designing physically based models in the first place. This method assumes that the response of the whole can be modelled by aggregating the response and behaviour of the parts. This thesis suggests that such a simple aggregation is not appropriate, and as Klemeš (1983) and Dooge (1984) have both stressed, a more fruitful way forward would be derived if a new set of laws were derived which relate to the catchment scale. Physically based models should therefore not be forced into either practical or indeed, scientific applications if they are demonstrated not to be conceptually suitable.

Whilst this thesis has emphasized that the suitability of physically based models for practical application needs to be evaluated. It is also suggested that in parallel, there is a need to explore new and innovative approaches to hydrological modelling for both scientific and practical application. In the context of this suggestion, it is timely to consider a quote from de Bono (1967) and which James (1982, p308) has referred to:

> "Logic is the tool that is used to dig holes deeper and bigger, to make them altogether better holes. But if the hole is in the wrong place, then no amount of improvement is going to put it in the right place. No matter how obvious this may seem to every digger, it is still easier to go on digging in the same place than to start all over again in a new place. Vertical thinking is digging the same hole deeper; lateral thinking is trying again elsewhere."

James (1982) used this quote to emphasize that hydrological modelling could benefit from a good degree of lateral thinking. Benefits might be derived from alternative modelling strategies which are more suitable for application to ill-defined systems, from application or incorporation of stochastic modelling strategies, or from an alternative view of hydrological processes at a catchment rather than point scale.

It is suggested that advances in remote sensing of hydrological data and in developments in computer technology will together provide a catalyst for change in hydrological modelling. The implications of remote sensing and fifth generation computer technology for hydrological modelling will now be examined.

8.2.3 Remote sensing: implications for hydrological modelling

The increasing application of both aircraft and satellites to the remote sensing of hydrological variables has important implications for hydrological modelling, and in particular for modelling in ungauged catchments. Catchments may remain ungauged in the sense that detailed historical and current channel discharge information will not be available, but improvements in the reliability, spatial distribution, and range of hydrological parameters derived from remote sensing will increase the scope for modelling studies in these environments.

There have already been limited examples of the integration of remote sensing in operational hydrological models, (McKim et al, 1984), and specifically of the use of remotely sensed soil moisture information (McKim and Pangburn, 1985). The use of remotely sensed data in modelling exercises requires a good deal of reorganisation and manipulation of the raw data, and data management and analysis programs are currently available which will achieve this. For example, the Hydrologic Engineering Center, Davies, California, have developed a Spatial Analysis Methodology (HEC-SAM) which has the ability to transform any data into a Geographical Information System which can be accessed by many Army Corps of Engineers hydrological, economical, or environmental models.

Some particular aspects of remote sensing are of specific interest to hydrological modelling. For example, the measurement of soil moisture conditions on bare soils (Schmugge, 1978; Schmugge et al, 1980) and under vegetation cover (Jackson et al, 1982), and the possibility of developing soil moisture profiles and water storage estimates from surface information (Ayra et al, 1983) are certainly of interest. The use of airborne laser systems for the determination of channel and valley cross section measurement (Link and Collin, 1981), and the ability to distinguish frozen soils, surface temperatures, snow pack characteristics, land use, floodplain mapping, and physiographic characteristics of catchment areas are all important areas of development.

Remotely sensed data relate more to areas than to points and will thus provide a means of integrating several hydrological characteristics and the variability of these into one composite measure. This may require a development of new models which will use areal rather than point information and may provide the means to develop new hydrological laws at a catchment scale.

Remote sensing data also provides the potential to supply information for Geographical Information Systems. Indeed the value of such spatial data base management for distributed modelling has been examined by Gupta and Soloman (1977a) and Jett et al (1980).

8.2.4 Fifth generation computer technology: potential for hydrological modelling

Automatic program generation techniques are one aspect of fifth generation computer technology which could provide significant improvements in software reliability and a reduction of the time involved in programming and implementation of hydrological models. It has been stressed that by using conventional programming techniques, it is not likely that all software errors in large and complex simulation programs can always be removed. Reliability improvements may be achieved by developments in automatic programming, or software generation techniques. These are computer techniques which will enable conceptual mathematical model programs to be built automatically, thus eliminating programming errors, and speeding up the process of model coding. This will free the hydrologist from computational and programming problems of little relevance to hydrology, and allow more time and effort for the design and evaluation of more appropriate mathematical hydrological models. The tools and techniques of simulation are after all of a scientific nature. It is the application of these to practical issues in the real world which demands the undivided attention, expertize and experience of the hydrologist.

This thesis has emphasized that in operational decision making, clearly the most important element is the hydrologist. Hannaford and Hall (1981) have stressed that it is the hydrologist who has developed the model, who most clearly understands the limitations and operational constraints of the model, and who fully appreciates the impact of model and data error on operation. Application of any mathematical hydrological model, necessarily involves, "...the intangibles of his [the hydrologist's] professional experience" (Moore and Clarke, 1981, p1369). This thesis has stressed that it is essential that communication between model developer and user groups be improved and in particular that a good deal of advice and help is provided to the user for effective parameter estimation. Data error can have as much effect upon prediction accuracy as the model structure itself.

A second aspect of fifth generation computer technology is thus suggested as a possible area for future activity and progress. Proposals for a simple incorporation of guidelines and information to help the user in parameter estimation have been provided in section 6.2 (figure 68). These proposals were for the development of an interactive computer program, but they can be taken one step further to include the development of an expert system.

The expert system is one example of the application of artificial intelligence and fifth generation computing to commercial and scientific areas. It is proposed that expert systems have a potential application in mathematical hydrological modelling as a means to operationalize simulation models.

Until recently, computers have been used for number crunching exercises, for data base management, and for numerical calculation. Research in artificial intelligence has provided the computer with increasing abilities in learning, associating, and inferring. Expert systems are computer programs which contain expert level knowledge of a specific subject area and which can provide, based upon this knowledge and a method of inference, expert level solutions to problems and questions which are posed by a less informed user.

In particular, an expert system may be defined as a computer program which:

- contains organized knowledge pertaining to a specific subject area, or domain, which is known as a knowledge base.

- contains a control strategy or inference procedure which manipulates and searches the knowledge base in a manner designed to parallel the reasoning process of an expert in the particular domain. The expert system therefore provides a skillful and effective consultancy facility. Two examples of control strategy include forward chaining, where the reasoning process progresses from data to hypothesis, and backward chaining, where attempts are made to find data which will either prove or disprove a particular hypothesis.

- is interactive and designed to provide a friendly and useful interface between the user and the program. A user contributes certain information, and the program combines this in a coherent and sensible analysis.

In addition, a more highly developed expert system may also:

- be transparent and open to interrogation. A user can query any decision which the system provides, and the system is capable of providing an explanation, in conversational rather than computer language, for the line of reasoning which it has adopted.

- be flexible. It contains a knowledge base editor which allows new knowledge to be integrated incrementally into the existing knowledge base.

- allow for the treatment of imprecise or incomplete rules and the manipulation and combination of these. Expert knowledge is most commonly ill-defined and heuristic, it rarely involves well formalized or numerical reasoning. Heuristic reasoning is essential for intelligent problem solving in many areas including hydrology and uncertainty may be treated by the applications of methodologies such as Boolean logic, fuzzy logic, or certainty factors.

Expert systems thus have certain advantages to offer mathematical hydrological models. Firstly, in practical and routine application of hydrology, there is a need to disseminate or replicate the human expertize of the model developer to potential users. In particular, this expertize and experience would be highly valuable in parameter estimation. If this knowledge were to be commited to computer storage as a knowledge base in the manner suggested above, then the knowledge would be available to the user, even when the expert was not. In this way, computers assume a role of interactive support systems.

Secondly, a knowledge base and control strategy provide a clear record of the information required for handling a specific problem, and in this case, in the application of a particular mathematical hydological model. This will replace paper versions of handbooks, and manuals of operating procedures.

The expert system will not replace human judgement, but will aid problem solving and decision making in areas not easily amenable to precise scientific formulation (e.g. parameter estimation) and in the absence of an expert.

Buchanna and Duda (1983) provide numerous examples of applications of expert systems. For example they have been used for the description and interpretation of situations in chemistry, genetics, and medical diagnosis, the interpretation of oil well logs, and military situation assessment. They are also used to provide solutions which satisfy goals within certain constraints in electronics design, molecular genetics, and chemical synthesis. In particular, two applications in Civil Engineering can be mentioned. SPERIL II is an expert system for assessing earthquake damage of existing buildings. PROSPECTOR (Dudda et al, 1979) is an expert system which analysises geological data to aid mineral exploration. Finally, one application in hydrology can also be mentioned. HYDRO (Fenves et al, 1984) is a recent version of the Stanford Watershed Model which has been developed into an expert system designed to help the less expert user assign parameter values. The knowledge base has been built up from knowledge which Crawford, one of the originators of the model, has gained during the twenty years since the first version of the model was formulated.

If expert systems are to be able to assume a role in the dissemination of knowledge about a model, this knowledge needs to be compiled. A thorough model evaluation, and a well constructed research design therefore becomes essential. The problem of conveying uncertainty and error in results is an issue which must also be approached, and in this context, Weber et al (1973) have raised the issue of the legal standing of models.

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